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Co-evolving with Material Artifacts: Learning Science through Technological Design[1)]

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ABSTRACT

Recent studies of science and technology "in-the-making" revealed that the process of designing material artifacts is not a straightforward application of prior images or theories by one (or more) person(s) isolated from his or her (their) environment. Rather, designing is a process contingent on the social and material setting for both engineering designers and students. Over the past decade, designing technological artifacts has emerged as an important learning environment in science classrooms. Through the analyses of a large database concerning an innovative simple machines curriculum for sixth-and seventh-grade students, we accumulated valid evidence for the nature of the designing process and science learning through it. In this paper, we show that design actions intertwine with the transformation of the objectified raw materials and artifact, the designer collective, and the mediating tools enabling that transformation, which constitute the elements of an activity from the perspective of cultural-historical activity theory. We conceptualize the continuous change of relation between material artifacts, designers, and tools throughout the design activity as co-evolution. Two episodes were selected to exemplify synchronic and diachronic change of relations inherent in co-evolving activity system. Finally, we discuss the implications of co-evolution during design activity for science learning.

Key words: technological designing, material artifact, co-evolution, cultural-historical activity theory

I. Introduction

Designing artifacts constitutes an important environment for learning science (Cajas, 2000); it has been regarded as a symbolic activity in engineering technology, which has a place and function resembling that of the experiment in science. Since the traditional demarcation between science and technology has become ambiguous and even dubious, and since the effort to involve technology in science education has been made for some time (Layton, 1993), it is reasonable for designing to be a constitutive part of science learning environments (Roth, Tobin, & Ritchie, 2001). However, despite several decades of research, many questions remain about the importance of engaging students in experimental or design practice and how conceptual learning

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happens when students engage in practical actions.

Science educators and teachers have long held the belief that students cannot understand science without knowing how the world works. Beginning with Armstrong's "heurism" during the nineteenth century (Jenkins, 1998) and including the "enquiring laboratory" in 1960s (Schwab, 1962), many arguments have been put forward in favor of laboratory work, which is said to support students' science learning and their development of autonomy (Hodson, 1996). Taking a constructivist approach, some science educators suggested that students need opportunities to experience what they are to learn in a direct way and that they need time to think through and make sense of what they are learning (Tobin, 1990). In many countries, inquiry and investigation are inscribed in the contemporary national curriculum of science. Yet a good theory directly linking specific hands-on activities, the skills that students develop, the corresponding scientific concepts involved, and the nature of world remains to be developed (Roth & Welzel, 2001).

Studies of technological designing seem to have been more successful in revealing learning through practice than those concerned with school science experiments or inquiry. Accordingly, technological designing is a situated and distributed process (Roth, 1996) that allows learning-in-practice as students pursue goals of their own interest (Roth, Tobin, & Ritchie, 2001). Design tasks themselves are not well suited for *transmitting* specific facts; rather, they provide opportunities for participating in activities central to design practice, including designing and testing artifacts, generating hypotheses, making presentations, and describing systems (Kafai, 1994). Students come face to face with scientific culture in the tools they use, although the latter cannot ever *determine* what students learn. Because of the generally unstructured nature of the tasks, designing provides students with opportunities to engage in specifying goals, framing troubles and breakdowns in the pursuit of these goals, and finding resolutions that allow a continuation of the main design activities. Some research showed that in open-design classroom communities, new forms of science and design language evolved and circulated among students (Roth, 1998). These results imply the contribution of technological designing to understand the unique features of learning through practice as a non-deterministic and indeterminate process.

Designing refers to not only the activities of producing artifacts, but also the process of arranging elements to form systems, including the design of experiments involving the configuration of procedures, detectors, instruments, and material configurations (Roth, 2001). During designing, the most noticeable change is the transformation of raw materials into a material artifact. Analyses of scientists' work show that this transformation does not arise from the straightforward application of image or concept in the head but from the continuous interaction of designers with their social (disciplinary) and material world (Pickering, 1995)-although these interactions are usually left out in the reports describing the outcomes of the scientists' work (Gooding, 1990). In everyday praxis, designing engages more than one designer; it is often based on the social interactions within a group of designers working on a common object (Bucciarelli, 1994). These interactions do not happen with empty hands and in empty space; designers always use tools, material or conceptual, in a social and therefore socially constrained environment. That is, designing and learning become comprehensible only when all these elements are considered together. Therefore, the purpose of this study is to investigate the transformation of elements of designing by focusing on their relations with the concurrent evolution of the material design artifact. We discuss the implications of our analysis for science education from the perspective of cultural-historical activity theory (Engeström & Miettinen, 1999), which we take as a heuristic for understanding the dynamics of the systemic relations and development of design activity.

II. Research Design

This study was conducted in a split sixth- and seventh-grade classroom, with ten students at the lower grade level (5 boys, 5 girls) and sixteen students at the upper grade level (7 boys, 9 girls). The students attended a suburban school in a predominantly white district of a racially mixed metropolitan in Canada. For most students, English was the first language, but six students were from different ethnic background and spoke a language other than English as their mother tongue. Two teachers team-taught the class. The regular homeroom teacher took responsibility largely for disciplinary and organizational issues. Roth planned the curriculum, conducted whole-class discussions, presented theories and scientific representations, and advised students on conceptual issues.

The "Simple Machines Curriculum" was designed to provide students with opportunities to learn science by designing and building machines. Consequently, students spent 60% of this 36-lesson unit on designing, building, and presenting machines (about one hour per lesson). The remainder was spent on hands-on activities specifically designed to give students exposure to the standard resources (tools, materials) of physics concerning simple machines (25%) and whole-class discussions that focused on force, torque, energy, work, and structure of simple machines (15%). All activities therefore provided opportunities for students to do and talk physics and engineering design.

Over the course of the unit, students designed four hand-powered machines-we understand designing to comprise all steps from initial ephemeral ideas over pencil drawing to the building and refining of prototypes. The first three machines were designed to lift loads, move loads over a long distance, and move loads by means of a self-propelling mechanism, respectively. In the fourth machine, students were asked to combine a minimum of four processes, two of which were based on the simple machines discussed in the unit.

The design activities were written in the form of requests for proposals (RFP). The fictional company "Northern Explorations Limited" needed specialized, hand-operated machines that could be used when their personnel experienced power supply problems while working in the Arctic. In the second design task, students were invited to design a machine that allowed the company to move heavy loads between two points of the company's exploration site. The RFP asked for a working model at least 2 meters in length and a proof that the machine actually decreased the effort force.

Three research assistants collected data in an ongoing manner. All lessons were continuously recorded using two cameras. During whole class activities, the second camera served both as a backup and as a means to improve the recording of student talk everywhere in the classroom. In addition, two audiotape recorders were used to capture (a) student talk during presentations, (b) teacher-student interactions, and (c) interviews conducted by a research assistant while students worked on their design projects. We collected students' notebooks that contained their paper-and-pencil designs, photographs of the artifacts they produced, and glossary entries that they constructed of their own choice for some key terms used during the design activities. In addition to the taped records, ethnographic observations were documented in field notes and in photographs. The teacher-researcher (Roth) was debriefed after each lesson; these debriefing sessions were documented in field notes. The planned curriculum, all curricular materials, and the artifacts used during teaching became part of the database. All curriculum planning meetings and interviews were recorded.

Both authors viewed the videotapes repeatedly, both individually and collectively, with the intent to come to a better understanding of the design process. Our analysis was informed by the method of Interaction Analysis (Jordan & Henderson, 1995), whereby researchers interact with one another to analyze interactions recorded on videotapes. In our individual and collective analysis sessions, we formed initial hypotheses that we sought to confirm or disconfirm in subsequent analyses or by running them by one another. Our results emerged from repeated cycles of generating, refining, and discarding working hypotheses. In the process, we generated many written analyses of different episodes. From all recorded designing sessions, we ultimately selected an exemplary one featuring two sixth-grade boys (Dave, Jon) for in-depth analysis, which literally involves moving image by image through the four-and-one-half hour design activity. We selected two episodes as typical cases from our repetitive passes through the entire database to represent two aspects of co-evolution, while capturing the characteristics of all data.

Ⅲ. Case Studies

Cultural-historical activity theory, initiated by L. S. Vygotsky and further developed by A. N. Leont'ev (Engeström, 2001), articulates human activity as an object-oriented, culturally and socially mediated system, involving division of labor and rules that mediate the interactions between the members of a community of practice (Miettinen, 1998). For example, in the following two episodes of this section, Jon and Dave ([collective] subject) are in the process of designing a simple machine from wood, Popsicle sticks, and shoelace (object). They use a spring scale, glue gun, glue, and language (cultural means) in the context of a classroom community (teacher, classmates) that mediate the nature of the activity (designing machines). Jon and Dave are sixth-grade students' assisted by the two teachers (division of labor)-participating in the science class and, accordingly, are held to carefully using circular saws and electrical drills, complete particular tasks on time, and respect classmates (rules). Figure 1 is a heuristic for articulating the structure of a design activity system in terms of six, characteristic structural elements (Engeström, 1987). This model of activity system has to be understood dynamically, as the system and its constituent parts continuously change (Roth, 2004); we conceptualize this continuous change of all parts as *co-evolution*. In tracking co-evolution of constituting elements of activity system, we start from the material artifact, one of the six structural elements.

During designing, the material artifact continuously changes; at each moment, the artifact constitutes a different configuration than during the previous moment. However, the different configurations are not separate entities but are related historically along the time axis: each configuration emerges from previous ones as the result of some transformation and therefore is contingent not only on its predecessor but on the entire design history. Furthermore, the change from one configuration to the next is not a simple (mathematical, conceptual) transformation. Each change in fact involves a practical action-an interaction of the designers with the material

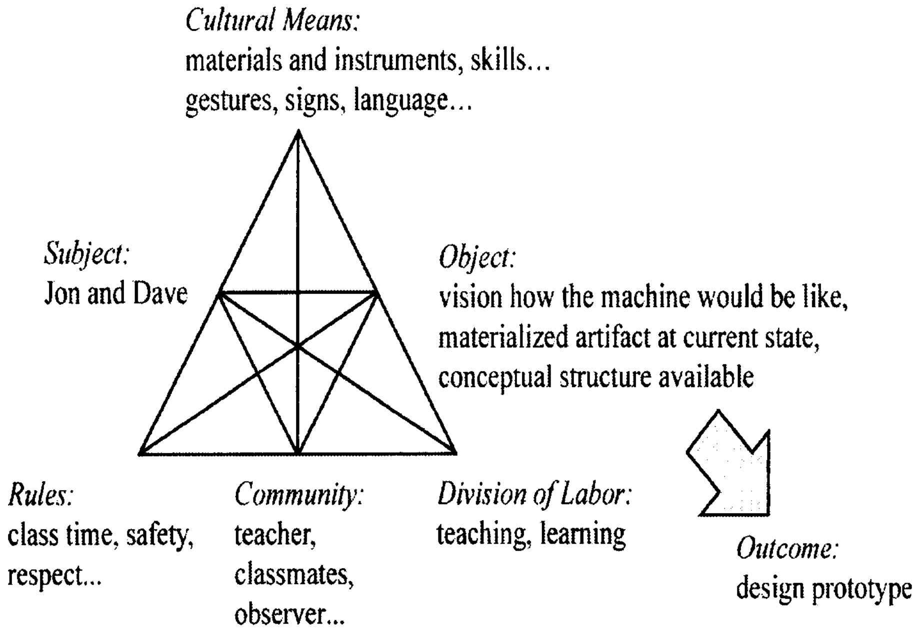

Fig. 1. An activity system of designing in science laboratory. The cultural means include tools for turning ideas into materials, including raw materials and instruments, as well as communication tools such as gestures and language. Focused on the subject-tool-object relation, object has three layers; the vision of human agency, the artifact of material agency, the conceptual structure of disciplinary agency. Contradiction in and between elements entails the historical change and development of this unit.

artifact-that is mediated by the tools at hand and occurs in some material and social setting, which supports and constrains the designing process. At each moment, the relations among the salient elements of the designing situation (including the material artifact) also constitute different configurations in a metaphorical space (see Figure 1). Therefore, the analysis of the transformation of a material artifact with its co-evolving elements requires the attention to the two axes-space and time. Focusing on the former provides the understanding of comprehensive relations between material artifact and other elements (*co*-evolving) on relatively shorter time-scales (milliseconds to seconds); the latter provides the understanding of longitudinal transformation of partial relations (co-*evolving*) on relatively longer time-scales (minutes to days). Both are complementary aspects of co-evolution. We describe and analyze the following episode with a focus on comprehensive relations on the micro time-scale, and extend our focus onto the macro time-scale, that is, to the level and whole activity levels. In the subsequent section, we focus on those aspects that are not revealed in this case study.

Episode 1 Jon and Dave work on a machine in the classroom. The machine is built from an approximately thirty-inch board, two vertical posts at either end, and horizontally fixed Popsicle sticks on top of each post. In front of the machine, Jon presses and rubs the joint of Popsicle sticks on the post, and then shakes the end of sticks slightly up and down. He untangles a shoelace and encloses it around the

Popsicle sticks. Dave brings a wooden weight and comes up to Jon.[2]

01	Dave:	It' s one hundred.
02	Jon:	Is it?
03	Dave:	Exactly.
04	Jon:	((After tying a knot in the shoelace surrounding Popsicle sticks, Jon pulls the shoelace back and forth with his hands.)) We shouldn' t use shoelaces.
05	Dave:	Well we' re just measuring it. ((Dave hangs the wooden weight in the middle of the shoelace. The weight stretches the shoelace down to the ground.))
06	Jon:	Okay now we need the scale again. Move that up. ((Jon moves the weight to the one end.))
07	Dave:	((Dave holds up the upper part of shoelace over the Popsicle sticks with his hand and makes a space.)) Well there' s going to be pulleys. ((Dave pulls back and forth the shoelace from which the weight hangs with his hands.))
08	Jon:	We can' t know but can' t be touching against the ground.
09	Dave:	I know we' re just using it to see-
10	Jon:	I know we need the scale so we can like pull this. ((Jon holds up the knot of shoelace, and simulates pulling movement of shoelace. He goes to get the scale.))
11	Dave:	Well just to see. ((Dave pulls the shoelace back and forth with his hands again.))

(a) (b)

Fig. 2. (a) A wooden weight stretches down to the ground; (b) Dave holds up one part of the shoelace as if there were a pulley (Episode 1).

In this situation, the two boys were in the process of preparing a test involving their design artifact in its current state. Their hand-powered machine was to provide a mechanical advantage; that is, they worked toward a machine that required them to use less force moving the load, a one-hundred-gram piece of wood, than if they moved it without the machine. After setting up the shoelace used for hooking ("tying a knot") and conveying the load and after conducting a trial movement (line 04), Jon appeared not to be satisfied with the shoelace ("We shouldn' t use shoelaces"; see Figure 2a). Dave emphasized that the current state of the machine

[2] The following transcription conventions were used.
((After tying...)) - double parentheses enclose comments by the transcriber, such as descriptions of ations; see - - n - dash at the end of a word indicates sudden stop of talk;
.;? - punctuation is used to indicate characteristics of speech production rather than grammatical units.

was not complete, articulating the situation as one in which they were "just measuring" (line 05). The two continued. They hung the load from the shoelace and then found that it stretched the lace down to the ground. Jon moved the load toward one of the posts, thereby bringing it off the ground, and uttered that they needed a spring "scale" for the next step (line 06). However, Dave held the shoelace over the Popsicle sticks, made a space between them, and said "there's going to be pulleys" (line 07) as if he could already see the pulleys attached to the Popsicle sticks (Figure 2b). He made a trial movement with the shoelace while keeping the space. Jon argued that the weight would not "be touching against the ground" (line 08), but Dave still wanted to "just" use the pulley "to see" how it worked (line 09). Leaving Dave-who was again pulling the shoelace back and forth-Jon went to get a spring scale (gauged in grams) that could be used to measure the force.

In this episode, the change of the configuration of the material artifact in itself appeared to be very simple; a shoelace was wrapped around the Popsicle sticks and a load was suspended from it. However, when the designers' hands met the material artifact, the changes were more than simple ones. For example, the configuration of the artifact changed according to the positions of shoelace and weight. With the same material artifact-while Jon held up the knot and simulated the pulling movement-Dave held the upper part of shoelace over the Popsicle sticks, made a space, and rocked the lace back and forth keeping the space. What made the difference here was that the different hand movements articulated different design visions; the different hand movements mediated the process of envisioning different future states. Jon's hand movement exhibited his vision of a subsequent action, that is, hooking a spring scale to the shoelace and pulling it to measure the force; Dave's hand movement exhibited his own vision of a subsequent action and design state, that is, putting pulleys on the Popsicle sticks and pulling the shoelace. Though *simultaneous*, the different hand movements therefore mediated *different* visions. Despite the fact that at any instant the artifact existed in but one material state, it enabled the designers to envision different possible next configurations. The hand movements and the associated visual imagery embodied and articulated these visions.

These visions of future states did not appear out of the blue. They were mediated by the hand gesture, the materials such as the shoelace (which would not be part of the final design), and the language used (e.g., the "pulleys" that Dave articulated as if he could see them). All of these elements constitute resources for designing as a distributed rather than purely mental process (Roth, 1996). In this episode, the shoelace was a mediating tool that both constituted the machine in its current state and, combined with gestures, the vision of its future state. It was a tool that was used although the designers quickly recognized its shortcomings (line 04). The "pulleys" constituted a rather different kind of tool. They were not material at all. In this episode, they existed in the form of language, and perhaps as some ephemeral visual image. To Dave, however, this language was already associated with a different form, because in his vision they operated like the material pulleys.

The different envisioned design possibilities arose from the interaction of the designers with their artifact; they even attained a certain level of materialization through historical transformation. For example, Jon and Dave's configurations of the material artifact with their hand movements came from the material condition of the load stretching the lace down to the ground. To use another example, Jon chose a shoelace as the material for hooking and conveying the load; but apparently, he did not envision how it would work until a knot was tied in the shoelace subtended by the Popsicle sticks and until the shoelace was moved back and forth. That is, the configurational change in the material artifact unfolded opportunities and even the necessity for new visions. Although they were not satisfied with performance of the shoelace, Jon and Dave continued using it for articulating their design. It was only much later that they replaced the shoelace with a smooth string. Therefore, to understand how the evolution of the material artifact brings forth the evolution of visions, and vice versa, we need to move beyond the current episode and analyze the designing process on a longer time-scale. We provide such an analysis in the next episode and the subsequent section; before moving on, however, we examine the change of vision and material artifact under one additional aspect.

The changes in the material artifact, brought about by hanging the load from the shoelace, had produced new possibilities. Here, it is important to note that there were differences in what the two boys considered as possibilities. Jon envisioned hooking and pulling a spring scale from the shoelace; Dave envisioned adding pulleys to the Popsicle sticks. However, though different, the two visions were complementary rather than contradictory. The two students cooperated as if one (collective) human subject had generated them. There was no salient evidence that the two students had different ideas about the artifact that they were in the process of designing. Dave weighed the load; Jon tied a shoelace around the Popsicle sticks. Dave suspended the load from the shoelace; Jon then changed its position. The two students acted as if they were one person, two individuals as structural composites of the dialectical unit of one collective designer of the same artifact. That is, the manipulation of the material artifact continuously provided opportunities to the group to reproduce itself as a collective designer all the while providing opportunities to each person to reproduce themselves as individual and separate designers-as in the case of different visions mediated by different hand movements. Simultaneously individual and collective subject-yet another source for contradictions-the boys were designing their machine. Yet at any one moment, proceeding required choosing one avenue, a collective movement toward the final artifact; if different visions became apparent, it was also evidence for a contradiction that needed to be resolved to allow continuation. Changes over longer inter-episode periods became apparent as we moved to Episode 2, which immediately followed Episode 1, that is, constituting the latter part of the artifact-testing episode.

Episode 2 Jon brings a spring scale and passes it to Dave. The latter attempts attaching it near the knot by twisting the shoelace. However, the knot is already near the Popsicle sticks: there is no room for pulling the lace because the knot would get hooked on the Popsicle sticks. Dave unhooks the spring scale from the shoelace, hooks it again to another part of the shoelace. He pulls the spring scale, but finds it slipping out of the shoelace instead of bringing forth the movement of the shoelace and load. By twisting the shoelace, Jon forms a loop, thereby allowing Dave to re-hook the spring scale to the shoelace and pulling again.

12	Jon:	Just pull it like that. No, wait, you gotta move it down. There's a knot in it. ((Jon moves the knot over the Popsicle sticks. Dave slowly pulls the spring scale with the right hand while pushing the joint with his left hand.))
13	Dave:	Three-fifty or so.
14	Jon:	Wait, just try it again. ((Dave unhooks the spring scale from the shoelace, hooks it the other end of shoelace again, and pulls it slowly. Jon turns the spring scale to read a

measurement.))

15 Jon: Okay when you tried to pull how much was it? ((Dave moves the spring scale backwards while hooking the shoelace. He pulls the spring scale with his right hand while pushing down on the left joint with his left hand. Jon stabilizes the other joint with his hands.))

16 Jon: Wait, okay, now stop. Okay it's three hundred, Dave.

17 Dave: It's three hundred.

18 Jon: Okay, now, um, Dave?

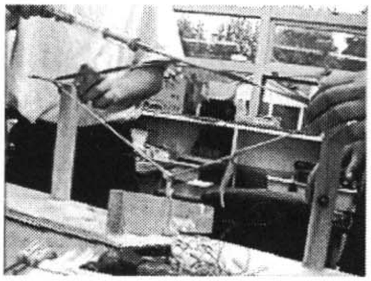

Fig. 3. Two boys are measuring the force required to move a wooden weight with a spring scale (Episode 2).

In this situation (Figure 3) again, the change in the material configuration consisted only in the addition of the spring scale; it was hooked to the shoelace and pulled to provide an indication of how much force was needed for moving the load. Notably, seemingly straightforward processes such as hooking and pulling were not performed simultaneously. At first, there was no room for pulling despite a successful process of hooking the scale to the shoelace. After unhooking and re-hooking the shoelace further away from the post, the spring scale slipped. In their third attempt, the students successfully moved the shoelace and load; but then, the knot got caught on the Popsicle sticks ("There's a knot in it" [line 12]). Besides, the joint between Popsicle sticks and posts looked too weak to be able to support the movement of the one-hundred-gram load. With one hand, Dave pushed down on the Popsicle sticks and against the post, as if he was making sure that the construction would hold up, while pulling the spring scale with the other hand (line 12). With some difficulties he pulled the spring scale from one end to the other end, and got "Three-fifty or so" as a result (line 13). It was so much compared to the weight of the load! Jon suggested trying again (line 13). Unhooking and re-hooking the scale the shoelace, they repeated the process (line 14). This time the graduation of the scale was on the back and could not be read. They had to repeat the test. Rather than unhooking and re-hooking again, Dave moved the spring scale backwards leaving it hooked to the shoelace. At last, they enacted a successful test, including the firmly hooked shoelace, a stabilized joint, and the graduated side of the scale in sight (line 15): they obtained "three hundred" as their result (lines 16, 17). Jon appeared to struggle with what to do next (line 18).

In Episode 1, Jon and Dave had produced different individual visions corresponding to the current state of the material situation. By bringing the spring scale and passing it to Dave, Jon transformed the situation into a test of the mechanical advantage provided by the machine in its current state, which was in line with his vision. Despite having had a different vision for a subsequent action, Dave joined in enacting the test that Jon had envisioned. In this, their visions cannot be said to be entirely different. They were already aligned, having a common object that framed their activity, and acted as a collective designer even in those moments that had started out with different visions. But to keep the designing process going, they needed to assure continued alignment and a shared vision and reproduced this vision in a more concrete way while satisfying the constraints of the current material condition. The salient aspect of this episode is the alignment between materials and tools, artifact, and Dave and Jon's skills in using and transforming them. In the process of aligning shoelace, spring scale, load, and their hands in the optimum way to make measuring the force possible, the two boys improved their skills of where to hook, how to hook, where to position the knot, where to hang, which side of spring scale to face, where to place their hands, and where to look at. As such, the test cannot be considered as having finished at once but as an extended process of alignment of diverse elements.

There was another reason for repeating the measurement-the "repetitions" were not mere repetitions but differed from one another. Jon and Dave were designing a machine that was to provide a mechanical advantage. The load weighed one hundred grams. Accordingly, moving the load with the machine should have required less than one hundred grams if their machine was to satisfy their intention. Initially they measured "three-fifty" (line 13). As soon as Dave had uttered, "Three-fifty or so," Jon said "Wait, just try it again" (line 14). They finished having measured "three hundred" (lines 16, 17). This meant that in their practical actions, they were oriented to not only the effective force measurement, but also the intended measurement of less than one hundred grams. The associated attention to attaching the spring scale, avoiding the knots, speed of pulling the spring scale, moment of reading the force, and force required for stabilizing the joint could not be separated from the action of measuring.

In this situation, the two boys were learning to embody the lowest force possible in the current situation. We suggest that any true, practical understanding of "mechanical advantage" involves all of these actions; the understanding of the "concept" of mechanical advantage does not exist independent of the experience of how mechanical advantage is measured and exhibits itself. But we know from the neurosciences that each practical action, each moment of cognition, changes our neural networks in however minute ways (Elman *et al.*, 1996). That is, every practical action that contributes to evolving the material artifact necessarily contributes to the evolution of practical knowledge and conceptual structures of the designers.

The two episodes analyzed here constituted brief moments in a long process of designing. In particular, these moments involved the first test of their emerging prototype. Seen after the fact, the test of the current machine might appear straightforward. Dave and Jon wrapped the shoelace around the Popsicle sticks glued to each of the two posts, suspended a one-hundred-gram load to it, hooked the spring scale to the shoelace, pulled the scale, read the scale as a measure of the force, and obtained three hundred grams as the result. However, our description showed that there was more to this test. The change in the material configuration that followed the initial actions entailed changes in the collective designer's vision, simultaneously articulating and evolving as a result of the mediation of hand gestures, materials, tools, and language. The practical actions on the material artifact-including materials and tools-gave rise to and were driven by the evolution of practical competence on the one hand, and the evolution of the conceptual structure on another hand. Any theoretical framework for designing needs to reflect such processes of co-evolution.

Ⅳ. Discussion

Cultural-historical activity theory provides an advantage over other approaches for understanding designing in that it constitutes a systematic view-each practical action is understood not as the result of something that occurs in students' minds but as the result of interactions and mediations within the system as a whole, including aspects of the social and material setting. However, each part of the system undergoes continuous change, as we showed in our analysis-another reason why cultural-historical activity theory, explicitly addressing the historical nature of every moment of practical action has turned out suitable to our endeavor of understanding the processes and products of designing. Given the diverse elements that simultaneously are accounted for in our basic unit of analysis (Figure 1), it comes as no surprise that contradictions can be found operating not only within some entity (e.g., different visions within the collective subject) but also between entities. Cultural-historical activity theory is suited to interpret students' actions in terms of contradictions; in fact, contradictions are the engines of changes within the system (Il'enkov, 1977). More recent analyses of scientific learning, discovery, and progress suggested that contradictions may arise from the interaction of three elements, subject, object, and tools (Gooding, 1990) and that these three elements could be regarded as human, material, and disciplinary agency (Pickering, 1995).

The second episode involves an example of such contradictions that arise from the interactions between the three layers that constitute the object of designing-what students intended, what they materialized, and what they conceptualized. These three layers, though pertaining to the same object, are categorically different and therefore inherently contradictory; they may also be misaligned, in which case there exists another contradiction. As these three layers of the object continuously interact with one another, the object moves into a new state until the intended and materialized artifact are in alignment. In the first episode, several contradictions are also found. First, after Jon finished setting up the shoelace in their machine (line 04), his vision was in contradiction with the current state of the material artifact. Second, when the wooden load was hanging down to the bottom of their artifact, Dave was envisioning the movement of machine with his invisible pulleys and hands (line 10), again giving rise to a contradiction between vision and current state. Finally, there also existed a contradiction between the visions of the two designers within the collective subject of the designing system.

In our approach, contradictions therefore do not have negative connotations; they are the sources of change, development, and expansive learning (Engeström, 2001). Because this (dialectical) approach inherently entails change in the form of a continuously evolving activity system, it embodies an explicitly historical and developmental rather than a static approach for understanding human cognition-at any point in time, we can understand cognition only when we study the trajectory of the system. In effect, activity theorists conceive of the basic elements in the theory and therefore the whole activity system as a continuously changing entity with continuously changing elements and interactions between them. From this view, we cannot say that the two episodes constituted a test of the material artifact or the designer's concept of mechanical advantage. What was tested, in fact, is the totality of the relations within and between elements constituting the specific activity system represented in Figure 1. There are three important consequences of such a perspective.

First, we suggest that these relations are the true foundations of the understanding of mechanical advantage that Dave, Jon, and their peers developed. Thus, these students knew more than the definition "mechanical advantage is load divided by effort" or, in mathematical terms, "MA = load/effort." For these students, the understanding of "mechanical advantage" involves all the traces that designing machines providing mechanical advantages will have left in them. It is in this way that these students can be said to have an "embodied understanding" (Varela, Thompson, & Rosch, 1993) of mechanical advantage.

Second, understanding Jon and Dave's actions not as a test of one variable but as a test of the whole system requires the consideration of historical change of activity system. As our episodes reveal, before the test defined in a very narrow sense occurred (line 16), there had already been various kinds of contradiction requiring the alignment of the object, intersubjectivity in the collective subject, and cultural means. Besides, even in its narrow sense, the test was a test of the whole system. When Jon and Dave produced "three hundred" as a final result of their test, it could have been a resistance to their conceptual understanding of "mechanical advantage," their vision, materials or instruments, signs or language, the intersubjectivity between the two boys, or the rules or division of labor mediating their relations in the community. These considerations raise doubts about the use of tests that science educators have used as part of hands-on and discovery science curricula and in the service of the hypothetico-deductive method, which has already been criticized in the studies of science on various grounds including the theory-ladenness of observation (Hanson, 1965), the philosophical Duhem-Quine thesis (e.g. Duhem, 1982), and results of ethnographic observations of scientists at work (e.g. Latour, 1987). The present study shows that however narrowly the practical learning situation focuses on the test of a theoretical hypothesis or on the appropriation of the hypothetico-deductive method, practical action always involves the system as a whole. Change therefore is the legitimate result of systemic contradictions: learning content and learning process constrain one another, or, in other words, the curriculum oscillates between the contents and processes of science (Gott & Duggan, 1995). From the perspective of cultural-historical activity theory, learning through practice includes more than the tension between contents and process; as was shown here, it involves the contradictory tension inherent in subject, object, cultural means, and social relations.

Third, the results of the testing episode may not have had an immediate impact on the unfolding process of designing. For example, Jon complained about the shoelace, but it was not replaced immediately. The two boys replaced it by a smooth string only in a subsequent test that followed those in the present episodes. Similarly, when their measurement result was "three hundred," they first had to align their different subjective understandings to become a collective subject. Their first action was to add more glue and construct a double-layered Popsicle stick part to strengthen the parts that the test had revealed to be weak. It was only much later that they added pulleys to the existing support. In designing, therefore, a test is not a discontinuous event separating actions sharply before and after the test. Rather it is a result of continuously unfolding contradictions inherent in the activity system and is always interconnected with other elements synchronously (**co-**) and diachronically (**evolving**).

V. Conclusion

In this study, we investigated the transformation of the material and social elements that constitute technological designing by focusing on their relations during the evolution of a material design artifact. Throughout the process of designing, the configurations of a material artifact evolved together with the collective designer's vision, the collective designer's conceptual structure, the available cultural means, and the intersubjectivity between two designers. From the perspective of a single designer, the co-evolution of these entities came in the form of continuous transformation (production) and reaffirmation (reproduction) of that which is other and thereby the transformation and reaffirmation of the self. Production and reproduction are both spatial (synchronous relations) and historical in nature (diachronic relations). From the perspective of cultural-historical activity theory, this co-evolution is understood as the self-transformation of an activity system driven by its own inner contradictions. In our case studies, the test of an artifact turns out to constitute in fact a test of whole activity system. The associated actions and their outcomes are accumulated within the system in historical time. This also implies that science learning needs to be understood both from a systemic, material, and social view and from a historical perspective that accounts for evolutionary events at the micro- and macro-time level.

References

Bucciarelli, L. L. (1994). *Designing engineers.* Cambridge, MA: MIT Press.

Cajas, F. (2000). Research in technology education: What are we researching? A response to Lewis. *Journal of Technology Education*, 11, 61-69.

Duhem, P. (1982). *The aim and structure of physical theory.* Princeton, NJ: Princeton University Press.

Elman, J. L., Bates, E. A., Johnson, M. H., Karmiloff-Smith, A., Parisi, D., & Plunkett, K. (1996). *Rethinking innateness: A connectionist perspective on development.* Cambridge, MA: MIT Press.

Engeström, Y. (1987). *Learning by expanding: An activity theoretical approach to developmental research.* Helsinki: Orienta Konsultit.

Engeström, Y. (2001). Expansive learning at work: toward an activity theoretical reconceptualization. *Journal of Education and Work*, 14, 133-156.

Engeström, Y., & Miettinen, R. (1999). Introduction. In Y. Engeström, R. Miettinen, & R.-L. Punamäki (Eds.), *Perspectives on activity theory* (pp. 1-16). Cambridge, England: Cambridge University Press.

Gooding, D. (1990). *Experiment and the making of meaning: Human agency in scientific observation and experiment.* Dordrecht, The Netherlands: Kluwer Academic Publishers.

Gott, R., & Duggan, S. (1995). *Investigative work in the science curriculum.* Milton-Keyes, England: Open University Press.

Hanson, N. R. (1965). *Patterns of discovery.* Cambridge, England: Cambridge University Press.

Hodson, D. (1996). Laboratory work as scientific method: three decades of confusion and distortion, *Journal of Curriculum Studies*, 28, 115-135.

Il'enkov, E. (1977). *Dialectical logic: Essays in its history and theory* (Transl. by H. Campbell

Creighton). Moscow: Progress.

Jenkins, E. (1998). The schooling of laboratory science. In J. Wellington (Ed.), *Practical work in school science: Which way now?* (pp. 35-51). New York: Routledge.

Jordan, B., & Henderson, A. (1995). Interaction analysis: Foundations and practice. *Journal of the Learning Sciences*, 4, 39-103.

Kafai, Y. B. (1994). *Minds in play: Computer game design as a context for children's learning.* Hillsdale, NJ: Lawrence Erlbaum Associates.

Latour, B. (1987). *Science in action: How to follow scientists and engineers through society.* Milton Keynes, England: Open University Press.

Layton, D. (1993). *Technology's challenge to science education: cathedral, quarry or company store?* Milton Keynes, England: Open University Press.

Leont'ev, A. N. (1978). *Activity, consciousness and personality.* Englewood Cliffs, NJ: Prentice Hall.

Miettinen, R. (1998). Object construction and network in research work: the case of research on cellulose-degrading enzymes. *Social Studies of Science*, 28, 423-463.

Pickering, A. (1995). *The mangle of practice: Time, agency, and science.* Chicago: University of Chicago Press.

Roth, W.-M. (1995). *Authentic school science: Knowing and learning in open-inquiry laboratories.* Dordrecht, Netherlands: Kluwer Academic Publishing.

Roth, W.-M. (1996). Art and artifact of children's designing: A situated cognition perspective. *Journal of the Learning Sciences*, 5, 129-166.

Roth, W.-M. (1998). *Designing communities.* Dordrecht, The Netherlands: Kluwer Academic Publishing.

Roth, W.-M. (2001). Modeling design as situated and distributed process, *Learning and Instruction*, 11, 211-239.

Roth, W.-M. (2004). Activity theory and education: An introduction. *Mind, Culture and Activity*, 11, 211-239.

Roth, W.-M., Tobin, K. G., & Ritchie, S. M. (2001). *Re/constructing elementary science.* New York: Peter Lang.

Roth, W.-M., & Welzel, M. (2001). From activity to gestures and scientific language. *Journal of Research in Science Teaching*, 38, 103-136.

Schwab, J. J. (1962). The teaching of science as enquiry. In J. J. Schwab (Ed.), *The teaching of science* (pp. 1-104). Cambridge, MA: Harvard University Press.

Tobin, K. (1990). Research on science laboratory activities: In pursuit of better questions and answers to improve learning. *School Science and Mathematics*, 90, 403-418.

Varela, F. J., Thompson, E., & Rosch, E. (1993). *The embodied mind: Cognitive science and human experience.* Cambridge, MA: MIT Press.