WHEN STUDENTS ARE PUSHING THEIR HORIZON: DIALECTICAL CONTRADICTION OF DESIGNING SIMPLE MACHINES

How students come to know phenomena in terms of concepts and theories through hands-on activities remains one of the open problems in science education. In classical theories (e.g., Piaget), conceptual knowledge arose somehow through abstraction from engagement with the concrete, material world. In this study, we articulate micro-processes of learning in science by analyzing a large database constituted during a four-month unit on simple machines in a split sixth- and seventh-grade class. We develop a theory of designing by employing a dialectical view of human activity that explicitly combines the mental and material in the same, irreducible unit of analysis. The dialectical contradictions embodied by this unit, which we conceptualize in terms of resistances from the perspective of the first person, push the development of the (collective) learner (individual, group) ahead. Drawing on case studies focused on the historical development of design artifact and the role of enminded bodies in the process, we examine how resistance leads students to enact their lifeworlds different way. We conclude with a reflection on the contribution of our study to a non-dualist view of knowing and learning.

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Introduction

How do laboratory activities allow students to learn about material phenomena in terms of (non-material) concepts and theories? Because of its widely accepted importance and broad practice, research on students' learning through laboratory work has produced many results, but at the same time, it also revealed limitations of past approaches. Two critical arguments can be made. The first is about a black-box assumption that when students are situated in the specific laboratory environment designed in some way by curriculum developer or teacher, and then students show some achievement at the end, it is the evidence of curriculum effectiveness. Here, the salience is not put on what students have experienced in the process of involvement in the labwork but on the resultant achievement. It is an essentially deterministic (behaviorist) view whereby the learning environment determines what happens to individuals (and groups). However, learning rarely occurs in ways that teachers have planned, even if they are highly competent and if they work under the best conditions (materials, students in elite schools); rather the curriculum emerges from the students' contingent real-time interactions with the whole activity (e.g., Roth & Duit, 2003). The second critical argument is about a dualistic assumption: what students think in their heads is more important than what they do through their whole bodies, and thus the actions of the latter are just subsidiary to the former. However, even the actions that seemingly could come about only in the head such as arithmetic or graph reading are deeply embedded in the bodily experiences of the world (e.g., Lave, Murtaugh, & de la Rocha, 1984; Roth, 2003). Therefore, those two points imply that for deeper understanding of learning and development we need to look at what is happening in the classroom by both taking a first person perspective (Holzkamp, 1991) and by attending to students' bodily actions.

Studies on the relations between organism and environment have revealed the mutually constituting properties of the two and developed the notion of *lifeworld*, the environment in which an individual perceives and acts; thereby physical environment becomes functionally meaningful within activities (Agre & Horswill, 1997; Schutz & Luckmann, 1973). The learning environment is not a stable or objectively available entity of which relation to an organism can be decided a priori; rather, the identification of relations is an empirical matter, affording different salience to different individuals (Roth, 2000; Roth, Boutonné, McRobbie, & Lucas, 1999). Learning is, therefore, a matter of evolving not only the individual world but also the common worlds of different individuals (Roth, 1999). From a phenomenological perspective, because there is no perception without motion, what makes the salience is the bodily movement in the world (Merleau-Ponty, 1962). By means of engaging our bodies with the world we can expand the horizon of the lifeworlds, which appears as the evolution of collective lifeworlds. In this regard, the opening question can be rephrased as "how does the participation in laboratory activities lead students to enact their perceptual world in a way that they have not done before?"

In this study, we answer to this question by articulating micro-processes through which individual learners' lifeworlds evolve into expanded and overlapped collective ones. We take a dialectical perspective because it does not dichotomize learners and environment, and individual and collective (Leont'ev, 1978). At first, we introduce the concept of contradiction as a key to follow up the development of concrete activities, and then describe the dialectical evolution of lifeworlds by drawing on case materials that we singled out from the students' design activities.

Toward a Dialectical Understanding of Activity

We are in the science classroom where the sixth- and seventh-grade students learn about simple machines such as pulleys, levers, cranks, and inclined planes—the cultural devices providing mechanical advantage when people move heavy loads. In response to request for proposals published by a fictional company, the students are designing machines —we understand designing as comprising all steps from initial fleeting ideas over pencil drawings to the building and refining of prototype artifacts. The following episode[1]

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[1] We used the following transcription conventions:
* – denotes the moment in the transcript that corresponds to the video off prints [Figure], which we put in series to provide the data set of changing action. Each figure constitutes independent data that cannot be substituted by written description;
((Leanne grabs…)) – Salient and relevant actions are noted and are enclosed in double parentheses;
°If you want° – Words between degree signs are spoken with very low, almost unnoticeable voice;
[– Square brackets in consecutive lines indicate beginning of overlapping speech or action;
(?) – Question mark in parenthesis indicates inaudible utterance(s);
so- – Hyphen at the end of a word marks sudden stop of talk;
ha::te – Lengthening of a phoneme is indicated by colon;
(sure?) – Indicates uncertain hearing of the utterance "sure";
↑no – The arrow indicates a rise in intonation sharper and more clearly noticeable than normally occur;
.;? – Punctuations are used to indicate characteristics of speech production rather than grammatical units.

occurred near the end of the four-month unit, while the students were working on their culminating project in which they combined a minimum of four simple machines into a "Googol-Plex-o-Saurus."

Episode 1 One sixth-grade girl (Amy) and two seventh-grade girls (Bella, Leanne) are working together around a table in the science class. Amy is *adding glue to the joint part of the wooden board and the paper tube *[Figure 1a]. Bella supports Amy by gripping the board upright with her right hand. Leanne has her gaze directly at the tube and board, moves back from where she is standing, then steps up to it again.

a. b. c.

Figure 1. a. Amy is adding more glue to the joint part of board and paper tube. b. Leanne is gripping the board upright with her right hand. c. Leanne is bending the tube downwards to show how it ought to be like.

01 Leanne: *Oh ↑no, no, [it's not diagonal.
[((Leanne grabs the board with her left hand, the tube with her right hand, and begins to bend tube downward.)) *[Figure 1b]
02 Bella: (Go?) to the left. ((Bella held the board with her right hand and pressed the tube against the board with the other.))
03 Leanne: Has to be like this* and then we nail it down. It is like this. *[Figure 1c]
04 Amy: I know, okay. Where do you want it? Yeah– at which side?
05 Leanne: It's okay! We nail it; we'll nail it on that (sure?)

In this situation, Amy was adding glue to the joint supported by Bella. Leanne moved from where she was standing, all the while gazing at the piece; she then noted that the angle between board and tube was not the way it was supposed to be, "diagonal" (turn 01). Just as she finished this utterance, she had come to take a hold of the artifact, her left hand stabilizing the upright board, the right hand grabbing the tube. She started decreasing the angle, bending the artifact at the joint. While Bella was holding onto the board and pressing the tube against the board, she was telling Leanne, "go to the left" (turn 02). Continuing to bend the artifact at its joint, Leanne uttered that it "[h]as to be like this," and that they had to "nail it down" (turn 03). At this point, Amy expressed her readiness to revise the configuration (turn 04), but Leanne continued to bend the configuration, pulling the tube with her right hand to decrease the angle and using her left hand to fasten the tube against the board, thereby stabilizing the existing joint (turn 05).

How shall we understand this situation? We begin by thinking about the *action* of gluing. Actions are accomplished by subject(s) in the pursuit of *goals*, which constitute the object of actions. Here, the goal was to fasten the paper tube to the wooden board and thereby to transform their common artifact from its present to some future configuration. The joint, which had already been glued, was strengthened. The three girls were participating in this action by adding glue to the joint (Amy), supporting the board (Bella), and looking at it (Leanne), respectively. Everything appeared to go well—at least until Leanne noticed that something was wrong in their artifact, "Oh no, no!" She was saying that the configuration was wrong because it was "not diagonal." But it should have been "diagonal."

Why should the configuration be diagonal? The response to this question requires an understanding of the *motive* of the whole-class, collective *activity*[2] within which the goal for the gluing *action* emerged. The above episode was a part of the class for implementing the last project of a unit on simple machines. The motive of this activity was to design a "really big machine" in which some initial action would trigger a series of events involving levers, pulleys, cranks, inclined planes, or elastics and springs. These three girls concretely realized the motive of activity by building their own Googol-Plex-o-Saurus. The motive (activity) and goal (actions) mutually constituted one another (the actions making the activity, but the activity giving rise to actions) or, in other words, motive (activity) and goals (actions) stand in a dialectical relationship. The girls' designing activity had begun with a brainstorming session about possible designs, which ultimately led to a paper-and-pencil drawing (Figure 2). At present, they were working on the part sketched in the upper left of the diagram (Figure 2) where a tube constituted an inclined plane so that a ball would, in scientific terms, change its potential energy into the kinetic energy as it was rolling down. That is, their intention was to have a tube-elevator angle of less than 90 degrees and therefore, to have it on a "diagonal." Leanne realized that the current right-angle configuration (Figure 1b) was in contradiction with their intention.

Then how did this contradictory situation happen? The gluing action was directed toward the goal of strengthening the joint; but making this joint and strengthening exist in their relation to the activity and its motive. The goal and motive are in a dialectical, mutually constitutive relation: the motive leads to goals but goals realize the motive. At the same time, gluing involved a very different dimension: it was accomplished through a series of unconscious *operations* that were driven by and oriented to the *material conditions*. For example, Amy was gripping the glue gun with her right hand, holding the tube with her left hand, and Bella was holding the board with her right hand to make it stand upright (Figure 1a). They did not think about how to grip the glue gun or how to hold tube and board—these constitutive elements of an action were unconscious. Yet these operations were not random: they were appropriately sequenced to accomplish the gluing action. Thus, between operations (conditions) and actions (goals) exists a dialectical, mutually constitutive relation: an action serves as referent to operations but operations realize the action. When the girls were adding glue to the joint, the configuration had already been fixed through the previous action thereby constituting the material condition. The shapes of board, upright tower, and paper tube had already preconditioned the right-angled joint.

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[2] In this study, the term activity is used to denote an entire system (e.g., Engeström, 1987)—including motives, tools, community of practice, division of labor, and rules—rather than a school task, which science educators have traditionally denoted by the term.

The given material conditions, regardless of the girls' initial intention, had an aspect of constituting the resultant action. Therefore, gluing had two different relations to the motive of designing (activity) and the material conditions (operations), constituting the intentional and operational aspects of activity respectively.

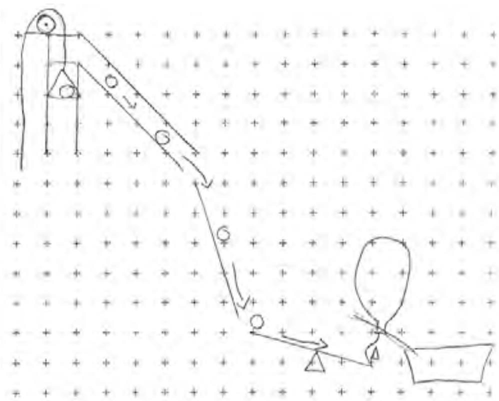

Figure 2. The drawing that Amy, Bella, and Leanne prepared as part of their project of designing a big machine so-called "Googol-Plex-o-Saurus."

Within activity, there always exist the possibilities of contradiction between intentional and operational aspects that are brought about and sustained by action. Contradictions between scientific designers' initial intentions and current material configurations are common in the material practices of scientists (Gooding, 1990; Hacking, 1983; Pickering, 1995). Importantly, contradictions have to emerge as problematic situations to the designers themselves so that it can lead to conscious change efforts. For example, in our opening episode, a science educator (teacher, researcher) may have immediately noticed the contradiction between the right-angled configuration in the artifact and the intended configuration realized in the paper-and-pencil drawing. Formulated in this manner, from an outside or third-person perspective, the contradiction does not enter (affect or mediate) students' designing. Instead, the difference between intention and current material condition has to be noticed at the inside of the design process, by the subjects. Thus, after the girls had spent nearly one minute adding glue to the joint, Leanne perceived the 90-degree angle and articulated it as incompatible with their intention. In the present study, we refer to incompatibilities or contradictions emerging from within a process as *resistance*, a category of a subjective, first-person perspective, and we distinguish it from *contradiction*[3], a category of a third-person perspective. Resistance denotes a

[3] Within a dialectical framework, contradiction is the central category denoting the unity of mutually exclusive opposites. Different from the logical contradiction, it is not a logical *a priori* but the theoretical expression of reality from the very course of the investigation (Il'enkov, 1977). Any concrete, developing system includes contradictions (an identity of the non-identical) as the inner force of its self-development. In human activities taking place in the lifeworlds (Agre & Horswill, 1997; Schutz and Luckmann, 1973), the contradiction emerges in different forms. From the perspective of structure, the object of an activity appears two times: one as a thing independently existing but selected to be the object of transformation (*Gegenstand*), and the other as an image of the object constructed by a subject (Leont'ev, 1978). From the

contradictory response of the objective material world to the designers' action for realizing their subjective intention. A person experiences this as a failure to realize what he or she wants, which therefore requires an accommodation.[4] That is, a person may not actually understand the structural conditions of the contradiction, but experience resistance and attribute it to something currently salient in his or her lifeworld—they treat symptoms, the thing they perceive and experience rather than the causes, which are revealed through a reflexive, distancing, third-person analysis. We understand resistance—the contradictions as seen from the inside, the inner contradictions—to be the true driving force of (designing) activity, which leads subjects to enact their perceptual world in a way that they have not done before.

Research Context

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 segment of a racially mixed metropolitan district. For most students, English was the first language, but six students were from different ethnic backgrounds and spoke a language other than English as their mother tongue. Two teachers co-taught the class. The regular homeroom teacher largely took responsibility for disciplinary and organizational issues; one of the authors planned the curriculum, conducted whole-class discussions, and advised students on conceptual issues related to science and engineering.

This curriculum on simple machines was designed to provide students with opportunities to learn by designing and building machines. Consequently, students spent 60% of this 36-lesson unit on designing, building, and presenting machines. The remainder was spent on hands-on activities specifically designed to give students exposure to the standard concepts of physics concerning simple machines (25%) and whole-class discussions that focused on forces, energy, and design 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 fleeting ideas over pencil drawing to the building and refining of prototypes. The design activities were written in the form of requests for proposals (RFP) made by a fictional company "Northern Explorations Limited" for specialized, hand-operated machines that could be used when there were power supply problems. 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. In the fourth machine, students were asked to combine a minimum of four processes, two of which had to be based on the simple machines discussed in the unit – levers, pulleys,

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perspective of agency (Sewell, 1992), it also appears as dual nature of subjectivity: one as an individual subjectivity, which always has the collective social nature and therefore appears as intersubjectivity on the other (Holzkamp, 1983). The contradictions inherent in those dialectical units drive the spatiotemporal unfolding of an activity.

[4] Consistent with a dialectical theory of human action (e.g., Pickering, 1995), we use the term accommodation to express the removal of resistance rather than the reconfiguration of conceptual structures (to which we have no access) that Piaget (e.g., 1970) had described.

cranks, inclined planes, and elastics and springs. Particularly in the second design task, students were invited to design a machine that allowed the company to move heavy loads between two points of their exploration site. The RFP asked for a working model at least two meters in length and a proof that the machine actually decreased the effort force.

Three research team members collected data in an ongoing manner. All lessons were continuously recorded using two cameras. During whole-class activities, the second camera served as a backup to record students' talk as completely as possible. In addition, two audiotape recorders captured (a) students' talk during presentations, (b) teacher-student interactions, and (c) interviews conducted by a research assistant in the setting as students worked on their design projects. We collected students' notes containing their paper-and-pencil designs, photographs of the artifacts that they had produced, and glossary entries students constructed of their own choice for some key words used during the design activities. In addition to the taped records, ethnographic observations were documented in field notes and in photographs. The teacher-researcher 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, accepting, disconfirming, or discarding working hypotheses. In the process, we generated written analyses of different episodes across the database. From all recorded designing sessions, we ultimately selected two exemplary groups, two sixth-grade boys (Dave & Jon), and three seventh-grade girls (Leanne, Bella, & Amy) for in-depth analysis. We analyzed moving image by image through design activity and transcribed the events.

Pushing the Horizon: Dialectic Dance of Enminded Bodies and Cultural Artifacts

Designing is a process in which initially ephemeral ideas come to be concretely realized in material form, comprising all steps from the discussing ideas over the drawing of a diagram to the building and refining of prototypes. The process is not linear, as all along the process, ideas come to transform in response to the contradictions related to their material realization. Therefore, every design action not only changes the design artifact but also provides possibilities for the horizon of (inter-) subjective lifeworld to change. In this section, we analyze the changes of design artifacts across different steps of the designing process, particularly focusing on the role of designers' enminded bodies.[5] We

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[5] We conceptualize an action as a movement of enmined body following the tradition of dialectical phenomenology (e.g. Merleau-Ponty, 1962). The action is a "bodily" movement as its orientation toward the sociomaterial world, which necessarily requires the bodily engagement (operation level), and at the same time, an "enmined" movement as its orientation toward a sociocultural motive (activity level).

present four claims with the evidence coming from the in-depth analysis of two groups—one (Dave & Jon) which developed the second machine and the other (Amy, Bella, & Leanne) which developed their fourth machine in the curriculum.

<u>Bodily action materializes subjective ideas within the collective designer</u>

Claim 1 *Gestures concretize the ephemeral ideas of the individual designer, which are also rendered in drawings, thereby materialize subjective ideas within the collective designer in an intersubjectively accountable form.*

Gestures constitute actions in line with the concretization of not only an individual designer's idea but also of the collective designer's idea. In their earlier step of design activity, two boys drew diagrams on their design pads, explaining to each other so that they could come to one design that would be materialized to the prototype. The following two episodes show the role of gestures manifesting in this process.

Episode 2 {November 2, 10:33 AM} On the first day of their second design project, Jon and Dave are talking about the *diagram that Dave has been drawing. *[Figure 3c]

a. b. c.

Figure 3. a. Dave is drawing his design on the paper. b. Jon is talking with his finger moving along the diagram. c. The diagram that Jon and Dave are talking about.

06	Dave:	*Up here could be the warehouse. Hook the weight onto there, it slides down there, hits that and slides into the truck. *[Figure 3a]
07	Jon:	But it needs to be a mechanical advantage instead of pulling it. We need to get it up there somehow.
08	Dave:	I know.
09	Jon:	How are we going to-?
10	Dave:	We use a truck. It goes up there, drops it.
11	Jon:	So don't we need two trucks? Use two ↑trucks? Like, okay, if you imagine this, [okay. We have a ramp *like this. This is like wood here. The truck comes up, puts that on here like that. Take the truck move it and this will come down, down like this. *[Figure 3b]

Concerning the dialectical relation between mind and body inherent in an action, there already have been many studies in the area of philosophy, language, psychology, and cognitive science, for example. The notion of "embodied mind" (e.g. Johnson, 1987; Varela, Thompson, & Rosch, 1993), and an understanding of the cognition as the situated and distributed action (e.g. Clancey, 1997; Lave, 1988) have been developed. For all their tremendous contribution to go beyond the dualistic split between body and mind, how "bodily" practice contributes to the development of mind, particularly what the micro-processes of changing actions are, remains vague. We see the concept of "enminded body" can compensate the blind spots of "embodied mind" perspective in this regard.

> [((Jon followed the diagram with his right hand, along the movement of a load in their machine.))

Dave added a warehouse on top of the ramp to the existing diagram. The load would come into the warehouse first and then slide into the truck along the ramp (turn 06). Jon asked how to "get it up there," "instead of pulling" so that the machine provided a mechanical advantage (turn 07–09). Dave suggested using an additional truck, one for uploading a load to the hill, the other for moving it at the end of the hill (turn 10). Jon looked confused. He repeated the movement of the load with his right hand, from the right side of the incline to the left, and then gave his consent by nodding his head and holding his thumb up (turn 11).

In this situation, Dave was elaborating his design by talking and drawing. Jon doubted if the design would provide a mechanical advantage. Dave answered to the question by drawing and talking again (turn 10), but Jon did not look satisfied with the current design in that his utterance, "Use two trucks?" (turn 11), implied his surprise. Here, Jon began to "imagine" (turn 11) the design by following the diagram with his right hand (deictic gestures). He enacted Dave's drawing through his body, thereby reconstructed the design through the talk and bodily movements (Figure 3b). Jon's gestures constituted a unit of the current design within the collective designer and thereby led him to get into the Dave's subjective idea and to share the perceptual world with him. Nodding his head and holding his thumb up implied that the current design was in line with his subjectivity and therefore existed in the intersubjectivity of the collective designer.

The gestures constitute one material form of design artifact that makes available one form of subjectivity to another because they not only reproduce the current design but also turn the subjective vision into the material form. We can see the more active role of enminded body in the iconic gesture manifested in the next episode.

Episode 3 {November 3, 11:21 AM} Jon and Dave are near to the last step of drawing. They draw and talk about the diagram to fix their *final design. *[Figure 4c].

a. b. c.

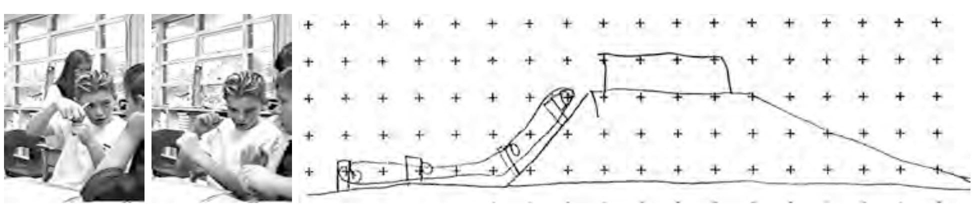

Figure 4. a. Dave is gesturing the shape of a paper clip that will hook a weight. b. Dave puts his two arms in series as if he held a clothesline in his hands. c. The final diagram comprises inclined planes, pulleys, posts, a string, and a garage.

12	Dave:	Okay there's like (???) comes down here and goes across and pulleys.
13	Jon:	How many are we going to have?
14	Dave:	We can get pulleys from (???). We can have- put the garage here and like when the truck comes, it pulls it up here, drops it off here, and then string right here.

15 Jon: Couldn't we hook it on?
16 Dave: Yeah, [1with a *paper clip, hook it on, it slides down here and it drops off.
[1((Dave gestures to indicate folding of paper clip.)) *[Figure 4a]
17 Dave: We can take it back. Just drops it off. We can take it back. Like you know when you do a [2*clothesline, you do it like that or we can just move this along here and then turn around.
[2((Dave puts his two arms in series to indicate a clothesline.)) *[Figure 4b]

Dave drew an inclined plane ("comes down here"), extended the horizontal line ("goes across"), and marked several pulleys ("and pulleys") (turn 12). Jon asked how many pulleys they should have if they would build the machine with real pulleys (turn 13). Dave drew the garage on top of the hill and one more inclined plane for the access of a truck ("the truck comes"). He explained the movement of a load from truck to garage ("it pulls it up here, drops it off here") and drew the string around the pulleys ("then string right here") (turn 14). As Jon suggested hooking a load to the string (turn 15), Dave talked about a paper clip (turn 16). Dave gestured the movement of a load along the ramp to the end of the plane ("it slides down here and it drops off") (turn 17). He continued that the string would move in a continuous manner like a clothesline, wrapped around two pulleys (turn 17).

In this situation, the two boys were drawing and talking about how a load would hang from the string, and how the string would move around the pulleys. They had already communicated their design before this conversation, and now there seemed no need to draw on their bodies as part of design. Therefore, at first, they structured their design usually through talking and drawing. They even rarely looked at each other but attended to the diagram together until Jon talked about how to hook a load (turn 15). Dave replied to Jon's talk by mentioning real materials such as paperclips and clothesline, rather than generic design elements. Here, there appeared gestures again as constituting part of design artifact (turn 16–17). Dave gestured the shape of paper clips that would hook a weight (Figure 4a) and put his two arms in series as if he held a clothesline in his hands. By means of iconic gestures, he not only enacted his subjective idea in a three-dimensional concrete form but also made it available to Jon in an intelligible way. It must be that what they saw was not simply a diagram but real materials and a movement of a load, which they had envisioned and materialized through their enminded bodies.

<u>Engagement of enminded body with cultural artifact reveals perceptual horizons</u>

Claim 2 *In changing the material form of design artifacts, gestures and bodily engagement with cultural artifacts make salient the contradictory understandings inherent in the cultural practice of collective designer, thereby reveals the perceptual horizons of designers' lifeworlds. The accommodation of resistance requires the replacement of bodily movements with the structured cultural artifacts, which emerges as the conscious transformation of design artifact.*

The movement of enminded bodies not only leads designers to construct the collective perceptual world but also provides opportunities to reveal the contradictory understandings inherent in collective practice. The contradiction emerged in designers' perceptual worlds (resistance) affords them a moment to be conscious of their perceptual horizon, which requires the next action accommodating the resistance. In the following three episodes, we can see the process of perceiving and accommodating of resistance unfolded through the enminded bodies with different tempo.

After Jon and Dave had came to their final diagram (Figure 3c), they began to transform their diagram into the three-dimensional artifact. Although they have articulated how each part of the diagram would be built up with materials (see Episode 3, for example), drawing a diagram is one thing, and enacting it to produce a prototype is another. The following episode occurred when the two boys began to construct the pulley part, just after they glued and nailed two posts at both ends of a wooden board.

Episode 4 {November 3, 11:47 AM} Jon and Dave are talking in front of their working machine, built from an approximately thirty-inch board and two vertical posts at either end.

a. b. c. d.

Figure 5. a. Dave is putting his hand up on the post with his index finger stretching out. b. Dave is making a round shape with his thumb and index finger. c. Jon is putting his hand on the board. d. Dave is holding two sticks on one post with his left hand, and then bringing two more sticks to the other post.

18 Dave: We can have pulley [$_1$*like, we've got like pulleys like. I've got toothpicks and we put toothpicks [$_2$like that and we will have [$_3$*pulleys like that.
[$_1$((Dave put his hand on the post with his index finger stretching out as if it is a toothpick.)) *[Figure 5a]
[$_2$((Again, Dave put his hand on the post with his index finger stretching out as if it is a tooth pick and shaking the end slightly this time.))
[$_3$((Dave *makes a round shape with his thumb and index finger in the place where the pulley would be in the empty space)). [Figure 5b]
19 Jon: Maybe we should get those [$_4$*dowels instead. *[Figure 5c]
[$_4$((Jon put his hand on top of the board.))
20 Dave: Yeah
21 Jon: Remember? ((They go to get supplies from the back of the room. Dave comes back with a handful of Popsicle sticks. Dave put two sticks on one post, and *holds them with his left hand, then two more sticks on the other side and sees how they look like. Jon is looking at Dave's hand movements.)) *[Figure 5d]

Dave envisioned and materialized what the next step of their design work would be, with his hand movements. His bodily gesture suggested a configuration constituted by toothpicks (Figure 5a) and pulleys (Figure 5b) (turn 18). Jon suggested they could find something like dowels instead of toothpicks using the same kind of hand gesture (Figure 5c, turn 19). As Dave responded positively (turn 20), Jon said "Remember?" thereby reminding Dave of what they might have been experienced together some time ago (turn 21). They went to the back of the classroom and found the Popsicles sticks instead of toothpicks or dowels. Dave put two Popsicle sticks in parallel on top of one post, thereby fitting them to the width of the post. Holding them with his one hand, he brought other Popsicle sticks to the other post (Figure 5d).

According to the diagram (Figure 3c), the design required pulleys on the upper part of a post so that they could enclose a clothesline around the pulleys along the inclined plane. Despite the previously articulated drawing, they did not know exactly what shape each part would ultimately take and what kind of material would replace it. The upper part of the post was "in the making" (Latour, 1987), and the two boys were in a situation not unlike those in which designing engineers find themselves inventing an artifact that heretofore did not exist (Bucciarelli, 1994). In this uncertain situation, Dave began designing with his hands, representing the configurations of toothpicks and pulleys in a three-dimensional space (Figure 5a & b). For Jon, the design was still underdetermined despite Dave's gestures and utterances, because they did not have the toothpick at this moment. Jon changed the design by suggesting, "those dowels instead," which must be wider and thicker than a toothpick (Figure 5c). The attention of the two boys focused on finding out an appropriate material to support pulleys. Among the available materials in the classroom, Popsicle sticks finally emerged as the better material to fulfill a particular task in the situation.

In this episode, contradictory understandings became salient between what they had envisioned and what is available, on the one hand, and between the two boys' subjective visions, on the other. The perceptual horizons within which their actions had unfolded became salient as the two boys began to enact the diagram with their enminded bodies. When they brought the Popsicle sticks as appropriate materials and replaced them with the configuration that they had ever constructed with their hands, they could constitute a three-dimensional design artifact, which resolved the contradictory understandings. Bodily gestures and manipulations of materials—engagement of enminded bodies with the sociomaterial world—mediated concrete realization of the artifact into the initial three-dimensional configuration constituted by appropriate materials. We see this as a process of pushing the horizon of not only individual designers' perceptual world but also of the collective one as well.

Not every contradictory understanding emerges and resolves in such a short time. We can see how the movements of enmined bodies are replaced by the structured cultural artifacts in more detail through the following two episodes (Episode 5 & 6), which occurred after the two boys had finished gluing Popsicle sticks and decided to test their first prototype to verify if it provided a mechanical advantage in its current state. The next episode occurred while the two boys were setting up the machine in preparation of the test.

Episode 5 {November 3, 11:52 AM} Jon encloses a shoelace around the Popsicle sticks and Dave hangs a one-hundred-gram wooden weight from it. The weight *stretches down to the ground. *[Figure 6a]

a. b. c. d.

Figure 6. a. A wooden weight stretched down to the ground. b. Dave is holding one part of the shoelace as if a pulley were there. c. Jon is simulating pulling movement of the shoelace. d. Dave is pulling the shoelace back and forth.

22 Dave: Well [*there's going to be pulleys. *[Figure 6b]
[((Dave holds up the left upper part of the shoelace over the Popsicle sticks with his hand and makes a space. He pulls back and forth the shoelace from which the weight hangs.))
23 Jon: We can't know but can't be touching against the ground.
24 Dave: I know we're just using it to see-
25 Jon: I know we need the scale so we can like pull this. ((Jon *holds up the knot of the shoelace, and pulls the shoelace back and forth. Then he goes to get the scale.)) *[Figure 6c]
26 Dave: Well, just to see. ((Dave repeats *pulling the shoelace back and forth with his hands again.)) *[Figure 6d]

Looking at a wooden weight stretched down to the ground (Figure 6a), Dave pulled up one end of the shoelace from the Popsicle stick and made a space between them. He said, "there's going to be pulleys" (turn 22) as if there were already pulleys (Figure 6b). While keeping the space, he slightly moved the shoelace back and forth with his right hand. Looking at this, Jon said that the weight would not "be touching against the ground" (turn 23), but Dave still suggested "just using" pulleys "to see" how it worked (turn 24). Jon pulled up the other end of the shoelace where a knot is located, and suggested pulling the knot with a spring scale (turn 25). Even without waiting for Dave's response, Jon went away to bring a spring scale (gauged in grams) so that they could measure the force (turn 25). Left by himself, Dave again pulled the shoelace, moved it back and forth, and spoke to himself, "Well, just to see" (turn 26).

According to their diagram, the weight should have hung over the ground so that it could move along the clothesline enclosing pulleys, thereby there would be a mechanical advantage in this machine. In this situation, however, the wooden weight stretched down to the ground contrary to what they had anticipated. The two boys perceived the obvious difference inherent in this configuration (resistance), and tried to resolve it with their bodily engagement with the machine and material artifacts. One the one hand, Dave's bodily gestures related the situation to the pulleys that had been even included in the diagram but not in the current configuration (turn 22). On the other hand, Jon's bodily gestures manifested that he wanted to pull up the stretched shoelace by hooking a spring scale on the knot of the shoelace (turn 25). Noticeably, the two boys' different bodily actions and engagement with the different cultural artifacts revealed that there were contradictory understandings within the collective designer. They were structuring their design artifact in different ways since they were trying to replace their enminded bodies with different cultural artifacts. In the process of trying to accommodate the resistance, there emerged another contradiction within their perceptual worlds (resistance), which made the horizons salient to the collective designer.

Reflexive movement aroused by enminded body changes the collective horizon

Claim 3 *As the human body that has become part of the design artifact moves away again from it, thereby remove itself from concrete envisioning states, the orientation of action toward the sociocultural motive becomes salient to the collective designer: therefore, the collective horizon of designers' lifeworlds transforms.*

Despite contradictory understandings within the collective designer, revealed through the different bodily actions in the previous episode, as soon as Jon brought a spring scale to measure the force, the two boys continued testing the prototype without attaching pulleys on the Popsicle sticks. The next episode exemplifies the continuity of the ongoing activity grounded in the materiality of actions—enminded human bodies and currently available material resources including the machine itself. However, this continuity afforded a possibility of discontinuity, which came about through the reflexive movements of (embodied) human mind when enminded bodies moved away from the engagement with sociomaterial resources and structural relations.

Episode 6 {November 3, 11:53 AM} 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 the load. By twisting the shoelace, Jon forms a loop, thereby allowing Dave to re-hook the spring scale to the shoelace and pulling again. *[Figure 7a]

a. b. c.

Figure 7. a. Dave and Jon are hooking a spring scale to the knot of the shoelace. b. Dave is pulling the spring scale hooked from the shoelace and Jon is supporting the other joint. c. Jon is pointing to the pulleys that they used in designing the first machine and Dave is looking at Jon.

27 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 his right hand while pushing the joint with his left hand.)) *[Figure 7b]

28 Dave: Three-fifty or so.

29 Jon: Wait, just try it again. ((Dave unhooks the spring scale from the shoelace, hooks it to the other end of the shoelace again, and pulls it slowly. Jon turns the spring scale to read a measurement.))

30 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.))

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

32 Dave: It's three hundred.

33 Jon: Okay, now, um, Dave? ((Jon goes back to their old machine and *points to the pulleys and Dave turns to and looks at him. Jon asks the teacher.)) Can we take these pulleys off? *[Figure 7c]

Hooking a spring scale to the shoelace, Dave slowly pulled it, but then the knot caught on the Popsicle sticks. Besides, the joint between the Popsicle sticks and the 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 made sure that the construction would hold up, while pulling the spring scale with the other hand (turn 27). With some difficulty, he pulled the spring scale from one end to the other end, and got "three-fifty or so" as a result (turn 28). Jon suggested trying again (turn 29). Unhooking and re-hooking the scale from the shoelace, they repeated the process. However, the graduation of the scale faced on the back, therefore invisible. Dave moved the spring scale backwards leaving it hooked to the shoelace (turn 29). The spring scale pointed three-hundred-gram equivalent force to move a one-hundred-gram mass (turn 31–32), which exactly indicated that the mechanical advantage (MA = load/effort) is much lower than one. They looked disappointed (turn 33). Jon went to their old machine and asked a teacher if they could take the pulleys from it (turn 33).

In this situation, the two boys needed to bring a spring scale into a part of their design configuration because they wanted to know if the machine would provide mechanical advantage. The spring scale exactly replaced Jon's bodily gesture that had manifested how to hook it to the knot of the shoelace (Episode 5). However, it was not just an addition of a spring scale to the existing machine. For the spring scale to work as a tool for measuring the force required to move a one-hundred-gram weight, it should be related to the existing structure through the engagement of enminded bodies. The two boys had to find where to place the knot, how to hook a scale to the slippery shoelace, how to stabilize the weak Popsicle stick, and how to pull the spring scale so that they could get a measure as little as possible. All those processes were realized through the collective actions of the two designers, such as grabbing, hooking, and pulling materials, thereby seeing and feeling the material phenomenon, which simultaneous gave feedback to them. The two boys' concrete actions structured the sociomaterial world by making relations between enminded bodies and cultural artifacts and between two enminded bodies.

After the iterative testing actions, the structured bodies and the machine produced the "three hundred" as a result (turn 31), and ended the test. The two boys unhooked the spring scale from the shoelace, stopped pushing the Popsicle sticks, and took their hands away from the machine. Now, the result implied that their machine required almost three times more force than the weight of the load; their machine did not provide a mechanical advantage. At this point, Jon left their current machine, went to their previous machine, and pointed to the pulleys attached to it. Dave also looked at Jon's action, waiting for the teacher's response to the question "Can we take these pulleys off?" (turn 33). Their bodily movements—Jon's deictic gesture and Dave's body orientation—showed that they perceived a pulley as an essential material for the mechanical advantage. It could happen after they engaged their bodies with the design artifact (prototype), replaced their bodies with the material artifacts and structural relations, and finally moved their bodies away from the structured design artifact (reflexive movement).

Throughout the activity, this was not the first moment at which the pulleys emerged as an important cultural artifact. As shown in Episode 5, Dave's bodily gestures had already enacted a pulley as constituting part of the machine (Figure 6b & d). However, it had not become salient in two designers' collective perceptual world at that situation. Contradictory understandings remained unresolved. By participating in the collective actions, which means by engaging their bodies with the common sociomaterial world, the contradictory subjectivities of two individuals could reach the collectivity.

Therefore, the engagement of enminded bodies with the sociomaterial world and the reflexive movement taken by moving their physical bodies away from that engagement brought forth the action orienting toward the motive of the activity (the mechanical advantage) and the collectivity (the necessity of pulleys that Dave had even suggested). The two boys' action explicitly manifested that they came to enact their lifeworld in a way that they had not done before, which we conceptualize the perception of resistance and accommodation, or in another way, the emergence of contradiction and resolution within the perceptual worlds: the two boys were pushing the horizon of their lifeworlds through their enminded bodies.

<u>Becoming part of and apart from the collective practice mediate the change of horizons</u>

Claim 4 *Within community, a more competent person's bodily engagement with the cultural artifact as part of the collective designer's practice constitutes resources that the other members can access later on even after he/she moves away from them, thereby mediates the transformation of collective horizon.*

With examples of the two boys' activity toward designing a machine that provided mechanical advantage, we analyzed how the engagement of enminded bodies with cultural artifacts and then the reflexive movement came to transform the structure of design artifact. We set an activity as a unit for understanding learning in that designers' bodily actions could be understood relevantly only from the dialectical relations with the sociomaterial conditions (operational aspect) and the motive of activity (intentional aspect) at the same time.

The space where the design activity unfolded is not empty; we saw that there already existed material artifacts such as pulleys, which came to gain cultural meaning within the collective designer by being related to the praxis of enminded bodies. Every bodily action is situated in the social space, from the small unit of collective designer to the larger society that they belong to. For example, we cannot understand the two boys' activity without consideration of the classroom where their activity unfolded, which we would call as "designing community" (Roth, 1998). If we zoom out to view the classroom level, we immediately see many interactions occurring between different groups of students or between students and teachers. In this subsection, we analyze those interactions with an example of a teacher and one design group through the lens of the movement of enminded body. It shows another aspect of the "changing horizon" through enminded bodies, which has not become salient in the previous episodes.

Episode 7 {January 9, 11:36 AM} Three girls (Amy, Bella, & Leanne) are in the middle of designing their fourth machine. They are cutting a wooden board in the classroom, required to transform their diagram into a three-dimensional design artifact. Amy takes the saw and gets ready to *cut. The teacher, passing by the three girls, sees what they are doing. *[Figure 8a]

a. b. c.

Figure 8. a. Amy starts cutting a wooden board. b. The teacher is holding down a board to assist Amy's sawing. c. The teacher is taking one of the C-clamps that had held the protective sheet of wood to the table.

34 Teacher: Why don't you, why don't you take one of the clamps? Why don't you take–?
35 Leanne: [$_1$Because, it gets in the way of the saw.
[$_1$((Amy begins sawing with light and slow pushing movements.))
36 Teacher: Oh. See like, like these guys. ((He points to the students in the group working just next to them on the table.))
37 Leanne: Our, our wood is thick. They don't have anything underneath.
38 Teacher: Yeah that's what you have to do. Or, really, really hold it [$_2$tight.
[$_2$((*He holds down the piece that Amy is sawing.)) *[Figure 8b]
39 Leanne: Can you please hold it?
40 Teacher: Like [$_3$this way is much more difficult.
[$_3$((He is holding the board.))
41 Leanne: [$_3$Just- ((Amy makes about three stronger pushing movements than before, but still lightly.))
42 Amy: Could you please start it- ((The teacher *takes one of the C-clamps that had held the protective sheet of wood to the table. Leanne bends forward to take off another C-clamp.)) *[Figure 8c]
43 Teacher: Actually, no, no, we just need one. They're (ity?) ((Teacher moves to the corner of the table.))
44 Leanne: All right, we can go with that.
45 Teacher: [$_4$°If you want you can do work there.° I find it much easier to work.
[$_4$((Teacher holds the board and the table.))
46 Amy: Okay, we'll do it.
47 Teacher: Okay, you wanna take a look here? ((Teacher then *begins to saw while the three girls watch.)) Now, one person [$_5$holds here so that you don't get switch– so that it doesn't move.
[$_5$((Teacher holds hands on to corner of piece, pulling motion, which moves the wood slightly. He moved away.))

In this situation, the teacher questioned the three girls "Why don't you take one of the clamps?" (turn 34). Leanne replied that the clamp hindered the movement of the saw (turn 35). The teacher illustrated what he wanted to say by pointing to another group (turn 36). Again, Leanne replied that another group was not holding a wood with a clamp, and therefore her group did not need a clamp, either (turn 37). Then, the teacher proposed to hold the board tightly with gestures and utterances (turn 38). Leanne asked him to help them do it (turn 39) because Amy had already begun sawing while holding the board with the other hand (See Figure 8a, turn 35) regardless of the teacher's proposal. The teacher held the other part of the board down to the table (turn 40), but only after a few light pushing movements, Amy stopped sawing and asked the teacher to start the cut. Rather than doing the cut, the teacher began to detach a C-clamp from the table (turn 42). Leanne also bent her body to take off another clamp, and the teacher told her they needed just one (turn 43). He set up the board and clamp at the corner of the table (turn 45), called the attention of the three girls, and started sawing (turn 47). He demonstrated sawing through his body movements together with some utterances, and then leaving the saw, began to move away.

The three girls had worked as a collective to design the fourth machine, the last project of the simple machine curriculum, and in this situation, they were sawing a wooden board to concretize their diagram into the three-dimensional prototype. Like a pulley in the previous episodes, a saw is a material (tool) with which human bodies can concretely interact, and at the same time it is a cultural artifact that has a particular usage in a specific context. For a saw to work for cutting a wood, it requires a designer to perceive it as a tool and to enact cultural possibilities inherent in it through concrete bodily actions. Community members do not always have the same embodied experiences with a tool not only because they have different trajectories of activities but also because the community constitutes a part of the wider society being influenced by and influencing it.

In this episode, the three girls did not set up the C-clamp for their sawing because of their prior experience—the C-clamp had gotten in the way of the saw (turn 35). They just put an unfastened board on the table. It was probable that the board would move, once they began to saw it. Because of his extended experience, the teacher could foresee probable problems, so he approached the girls. He suggested using the C-clamp to fasten the board to the table, and took a case of students who were sawing a board next to them (turn 36). That is, one group's bodily actions engaged with cultural artifacts constituted resources for another group's actions. It became clearer in Leanne's utterance, "they don't have anything underneath" (turn 37), which implies that she had already taken a look at their sawing. Rather than forcing the students to take a clamp, the teacher participated in fastening the board to the table by holding down the piece (turn 39–41, Figure 8b). His bodily action became part of the collective practice and thereby provided an opportunity for Amy to ask for help (turn 42).

Amy was sawing a board with her arm close to the table, so that the other free hand grabbed the wood on its unsupported end (Figure 8a). The teacher responded to Amy's request by turning his body to Amy's position, but instead of taking the same position, he changed the orientation of the wood and took one of the C-clamps that had held the protective sheet of wood to the table (Figure 8c). He moved to another side of the table, taking with him the board, saw, and C-clamp. There he set them up such that the right sawing arm would face away from the table, which allowed him to hold the piece with his left hand. He called the students' attention to this configuration and to his bodily actions with some utterances (turn 47).

Over many previous instances of sawing, the teacher had developed an embodied relation to the saw. This embodied relation would have constituted his own typical configuration of sawing with which he felt comfortable. When asked to help, the teacher transformed the existing material configuration into the one he was familiar with (Figure 8c). His movement to the other corner of the table allowed a new configuration of a board and a C-clamp so that the hands' movements became unobstructed. Obviously, the teacher's embodied actions constituted concrete realizations of a more advanced culture in a way adjusted to the three girls' design artifact and a classroom situation. He structured his sawing movements and the material configuration including a saw, a C-clamp, and a table.

For a competent person, like a teacher, sawing is an action that unfolds in the operation level, but for the three girls it was not a case. As soon as Amy began sawing, she perceived a resistance—she could not cut wood as was needed for the machine. The contradiction emerged in the perceptual world of the three girls, which required an accommodation. What the teacher did was to participate in their lifeworld, becoming part of collective material practice through his enminded body, thereby providing the three girls with resources that remained as traces, including visual images of sawing in praxis and verbal instructions, the cultural practice, which could be enacted through the enminded bodies of the three girls later on. We can see this in the next episode that occurred just after the teacher had moved away from the three girls.

Episode 8 {January 9, 11:37 AM} After the teacher moved away, Amy restarts sawing and then Leanne takes over. One piece of sawing is done. Leanne brings another board and *holds it to the table with the C-clamp. Bella takes a saw and gets ready to saw. *[Figure 9a]

a. b. c. d.

Figure 9. a. Leanne is sawing a board. b. Leanne is holding a C-clamp to the board and table for the next sawing operation. c. Leanne is talking to Bella about the size of the piece. d. The teacher is asking them about the line with his hand gesture.

48 Leanne: We have to saw this way, [$_1$we don't need the *sides up right, [$_2$we need small size, we need small size, oh yeah tall, it's OK. [Figure 9b]
[$_1$((Bella puts the saw at some point of the board))
[$_2$((Bella begins sawing))
49 Teacher: Do you *have a line that you want to saw along? [Figure 9c]
50 Leanne: We just want to saw, well somewhere around that, but it doesn't matter.

51 Teacher: Why?
52 Leanne: Because, it's just for the sides, like the ball falls on an inclined plane and these are the sides.
53 Teacher: Oh, OK, yeah, good, good, try to hold the stand on one line.

Amy continued sawing what the teacher had started, and then Leanne finished it. They needed more pieces for their machine, so Leanne brought another wooden board and held it with the C-clamp. Bella was ready to start a new cut from her opposite side. As she took a saw, Leanne told to her "We have to saw this way" with her gesture, thereby pointed where to saw. Bella put the blade at some point of the board, and Leanne said that what they were sawing would be "sides" so it should be "small.' However, Bella began sawing without change, and Leanne repeated they needed "small size." Soon, Leanne said "oh yeah tall, it's OK" as if she understood Bella's intention (turn 48). The teacher came up to them, and watched the sawing. He asked if they drew a line on the board to "saw along" together with his hand gesture (turn 49, Figure 9c). Leanne replied "it doesn't matter" (turn 50), "[b]ecause it's just for the sides" of "an inclined plane" (turn 52).

In this episode, we see the students concretely realizing the bodily movements that the teacher had provided as resources in Episode 7. Compared to the situation where a wooden board was not tightened up by the C-clamp, the bodily position and orientation in a new setting (Figure 9a) yielded the bodily movements that allowed effort-saving sawing. Leanne could press the board and table with the other hand, supporting an axis of sawing movement whereas Amy had to hold the board up without any support thereby could not concentrate the force on the sawing hand (Figure 8a). The teacher's actions were being completely replaced by the movements of students' enminded bodies. Furthermore, students set up the C-clamp again when they finished sawing and went to the next board (Figure 9b) as the teacher had shown to them before (Figure 8c). The students' bodily actions were concretely realizing the cultural possibilities inherent in a saw and a C-clamp (cultural artifacts) by replacing the teacher's practice with their own. The three girls' actions explicitly manifested that they came to enact their lifeworld in a way that they had not done before, by drawing on the resources the teacher had provided: they were pushing the horizon of their lifeworlds through their enminded bodies, and the teacher mediated the change of horizon by participating in their lifeworlds.

Students' bodily actions were not just the reproduction of the teacher's. Sawing actions did not occur without any reason during design activity; there was a motive to achieve through bodily practices, which requires alignment in concrete sociomaterial conditions. In this episode, as soon as the students became familiar with the culture of sawing, they began to attend to the size of pieces that they were cutting. Leanne talked about "small" size because the piece would constitute the "sides" of the machine. Bella kept sawing without attending to Leanne's utterance, which again provided Leanne with possibilities to understand Bella's idea, "tall" piece. Leanne and Bella were situating their bodily movements while keeping in mind what the ultimate design artifact would be like. Even the teacher's suggestion to draw a line on the board (Figure 9c) was readjusted by their image of the machine revealed in Leanne's saying, "it doesn't matter" (turn 50), "[b]ecause, it's just for the sides, like the ball falls on an inclined plane and these are the sides" (turn 52). The teacher again did not force them to draw a line at this moment, but his hand gesture (Figure 9c) constituted another resource that the students could draw on later. Through the movement of "enminded" bodies that kept the motive of activity in mind, students produced and reproduced cultural possibilities that the teacher provided with concrete actions: now they were pushing the horizon by themselves.

In this section, we analyzed two groups' design activities to understand how students come to enact their lifeworlds in a way that they had not done before. We showed that the collective designer came to enact material artifacts (e.g., a pulley, a saw) as a cultural artifact when they engaged their enminded bodies with the sociomaterial world directly or by the mediation of culturally competent person's embodied practices. We showed that the process of "pushing the horizon" unfolded in the sociomaterial space along the temporal steps constituted by engagement of enminded bodies and reflexive movement again, or in the wider context, by becoming part of collective material practice and apart from it again. As we named the title of this section, we metaphorically described this process as a "dialectic dance" of enminded bodies and cultural artifacts. Dance is a time series of movements of material configuration unfolded through the rhythm. We found out the rhythm of design activity and enculturation of mind from the historical "in and out" movement of enminded bodies, driven by the dialectical contradictions between subjective ideas and material configuration on the one hand, and between different subjectivities within collective designer or community members, on the other. Through the activity, there was a simultaneous double movement: enminded bodies structured the sociomaterial world (design artifact and collectivity) and cultural artifacts structured their lifeworlds, thereby pushed the evolution of horizon. In the next section, we discuss the implications of our analyses in the context of science learning.

Dialectic of Resistance and Learning in Science

The purpose of this study was to answer the question, "how does the participation in laboratory activities lead students to enact their perceptual world in a way that they have not done before?" In the previous sections, we showed that resistance constituted an internal force pushing the transformation of design artifact that we described as a dialectical dance of enminded bodies and cultural artifacts, thereby pushing the horizons of designers' lifeworlds within the culture of science and technology. What does the changing horizon of lifeworlds tell us about the role of resistance in science learning? The example of the two boys provided a rather explicit example allowing us to explore the meaning of knowing and learning about "pulley" and "mechanical advantage."

The two boys had already enacted pulleys in the beginning, by envisioning and materializing them through their enminded bodies and drawings. They might have chosen pulleys as part of their machine because they had a sense that pulleys would provide the mechanical advantage, or because pulleys were just available in their material world. Whatever the case is, the design that they constituted with their bodies and materials revealed what they had already known about the pulley and the mechanical advantage. The two episodes (Episode 2 & 3) showed that the two boys could deal with pulleys in the diagram level. The pulleys appeared as constituting part of in the diagrams (Figure 2c & 3c); there was a knowing in those situations. However, once they turn a diagram into a material configuration, it became soon apparent that what they had envisioned and materialized about pulleys did not make strong relations to the concrete material configuration that they had to deal with to realize their vision, in that they had to start from finding appropriate materials (Episode 4). The pulley was not strongly related to their motive ("mechanical advantage") in that they carried out the test without pulleys (Episode 5 & 6). Those relations could become stronger when they wanted to take pulleys off to draw them on for their current machine (Episode 6). After the test, the two boys' bodily movements exactly manifested the stronger relations of "pulley" (sociomaterial condition) to "mechanical advantage" (motive of activity). Throughout the process, two designers' enminded bodies constituted the center of changing design artifact, changing knowing, therefore learning and development.

Therefore, the meaning of knowing exists only in concrete actions that have a double orientation to the motive of activity and to the material condition. Meaning emerges from the relation between sense and reference; in doing something that has this double relation, meaning is enacted and therefore is both social and embodied (operation). Meaning therefore does not exist in entities (tools, artifacts, words, texts) but only in the dialectical relation of two relations associated with action. As the two groups' episodes showed, resistance brought forth a reflexive movement from the current action, leading them to compare the result of action with the motive of activity, and at the same time to compare the sequence of operations with an anticipated outcome; the revision of two relations produced scientifically legitimate actions. In our dialectical framework, learning scientific concepts or process skills denotes specific changes of students' action. Resistances opened up possibilities for designers to step back from the current situation and to revise their actions in a conscious way.

Throughout our analysis of design activity, there emerged three kinds of dialectic movements inherent in science learning mediated by resistances. First, resistance constituted a node of dialectic movement between a first-person (unmediated) and a third-person (mediated) relation to designers' lifeworld, which brought forth an "epistemic switch" leading designers to see the material configuration differently, and thereby to institute a change in actions. However, it was not just the change of mental image occurring in the head, but the result of dialectic evolution of double orientations, which an action has toward a motive and the material conditions within activity. Therefore, the relation between sense and reference constituted the second dialectic relation, unfolding the meaning of action through the time, which we call as learning the (discourse, material) practice of the existing science and technology culture. Third, resistance constituted a node of dialectic movement between culture of science and its concrete form embodied in individual designers. Designers drew on cultural resources—they came in various forms such as cultural tools, design object, and sometimes culturally more competent community members—through their bodily engagement to accommodate resistance.

Such a dialectical relation-centered view leads us to explain why the cookbook style labwork rarely gives rise to science learning: students enact operations without knowing the goals and even less the motives of activity. Operations contribute to the constitution of meaning, but only in the presence of goals and motives. Thus, operations contribute to the reproduction of scientific discourse and material practices only when they constitute part of an activity of which motive enables the superordinate reflections. Without a goal or a motive there cannot be sense, and therefore there cannot be meaning. Our study reveals that learning and development occur within activity, an indivisible minimum unit of analysis, which also supports many research results and teachers belief that students learn when they are involved in inquiry with a motive.

The dialectical view of learning necessarily requires a genetic perspective. It may appear that the experience of resistance is a momentary event, evoked during a brief instant when the subject perceives difference underlying a contradiction. However, it is important to note that the perception was possible because the subject had been engaged with the world in and through their actions, accumulated in ever so slowly changing practices, that is, the culture sedimented in the embodied operations of the individual. The accommodation of resistance is also a function of the historical trajectory of the design activity. The subjects do not revise their object when resistance is "injected" from the outside, such as through teachers who operate from a discrepant-event perspective. Learning, recognizable as changes in the conceptual tools that designers have ready to hand and as changes in the operations that enable particular forms of material practice, can only be understood from an historical perspective. This framework contrasts with what many researchers in science education have implied about students' practices by the notion of misconception or alternative conception. Our "resistance" is different from the "cognitive conflict," the basic strategy for "conceptual change." The advanced culture of science and technology does not compete with students' current practice, but provides resources of action when they appear to students as such in their lifeworld.

Coda

We began this article with the question, "How do laboratory activities allow students to learn about material phenomena in terms of (non-material) concepts and theories?" In response, we developed a form of analysis of students' designing and learning, which views human activity as a dialectical unit resting on the identity of non-identical material and non-material aspects. Laboratory work has been supposed to be an important part of science curriculum, but there has been little researches explaining why the direct experience of socio-material world enables learning in science. Our research focused on the movement of enminded bodies that are located at the center of perceiving resistance, that is, the emergence of contradiction in designers' perceptual worlds. As contradictions emerged within designers' lifeworlds, the design artifact changed, designers' bodily participation changed, and therefore the relations that their bodies made to both what they pursued (a sociocultural motive) and what they dealt with in the socio-material conditions changed, which was equivalent to learning scientific concepts. In this way, concepts and theories are always only part of situations, possible resources that become what they are only when they are part of some action.

In the present study, resistance means neither failure to gain something "being-out-there" nor conceptual conflict "in-the-head." Such demarcations become ambiguous, for there are only transformations of concrete actions by participants. Resistances no longer constitute problematic moments to be removed by a third person, but a moment of learning for an involved person. Our dialectic approach goes beyond the common dualistic view of practice, which entails an unsolvable learning paradox not only between the individual understanding and the legitimate understanding of science, but also between learning manipulative skills and learning scientific concepts. Practical action is always contingent because it deals with the world as it presents itself at the moment. In designing, this leads to a contingent development of the project, which takes a particular direction as a result of necessarily situated accommodation of resistance. From resistance and accommodation come changes in the form and content of actions—such changes constitute learning. Therefore, resistance and learning are contingent in nature, for we can never know when and in what way resistance emerges into the consciousness of the acting subject. Resistance and learning are not determined prior to the design activity, but contingently emerge during designing. This leads us to reappraise laboratory work in science classroom. Rather than trying to remove all conceivable moments of resistance from laboratory work thereby providing "sanitized" and "idiot-proof" prescriptions, providing acceptable motive and culturally rich conditions constitutes approaches that are more reasonable. In this way, students can become subjects who consciously experience and realize the dialectical evolution of activity in its relations to actions and operations.

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