ELECTRICITY BILLS AS BOUNDARY OBJECTS BETWEEN STUDENTS' MATHEMATICS AND THEIR CONTEXT

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This study explores the role of electricity bills as "boundary objects" within an extracurricular mathematical modeling camp for Grade 9 students in Mumbai, India. Drawing on Cultural-Historical Activity Theory (CHAT), the research analyzes how students navigate the discontinuity between school mathematics and the real-world context of electrical power distribution. Findings indicate that while students successfully utilized school-based mathematical reasoning to reverse-engineer billing procedures, the artifact remained socioculturally opaque. Yet, such matheamtically rich artefacts have a potential for supporting boundary crossing, though a complete crossing was not observed.

INTRODUCTION

The discontinuity between school mathematics and mathematics-in-context has been a problem of great concern, one that has been described and approached through many perspectives (Jurdak, 2006; Lave and Wenger, 1991; Williams et. al., 2001). One of the primary goals of mathematics education is to equip students with the skills needed in the real world and to make their mathematical knowledge relevant to their everyday lives or work (Niss, 1994). Research has shown that students struggle significantly—and are often unable—to deploy their mathematical knowledge in tandem with their contextual knowledge. Moreover, it has been shown that mathematics in everyday life and the workplace is qualitatively different from school mathematics (Lave and Wenger, 1991).

Many scholars have come to study such divides as *boundaries*—

> "a sociocultural difference leading to discontinuity in action or interaction. Boundaries simultaneously suggest a sameness and continuity in the sense that within discontinuity two or more sites are relevant to one another in a particular way." (Akkerman & Bakker, 2011)

In the realm of education, such boundaries are often viewed not merely as barriers, but as potential sites for learning. Individuals can overcome these barriers through boundary crossing. This crossing is not simply the transfer of knowledge from one sociocultural world to another, but an exchange which re-contextualizes the knowledge of both worlds through the other. This crossing is often enabled and supported by so-called boundary objects that exist at the intersection of the two worlds. Certain mathematically rich artifacts from real-world contexts can be situated as boundary

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objects between school mathematics and the context from which they originate. These artifacts are not made for educational purposes, yet they embed mathematical relations within them. For example, a road map with latitude/longitude grids embeds a Cartesian coordinate system (see Venkat and Winter, 2015).

In this study, I report on the use of electricity bills as a boundary object in mathematics instruction. I present episodes involving secondary students (Year 9) participating in an extracurricular mathematical modelling camp, where they were tasked with familiarizing themselves with real electricity bills. During this task, students generated questions based on their mathematical knowledge that pointed toward answers within the real-world context of the purchase and sale of electricity. In this report, I adopt an activity-theoretic perspective to elaborate on how the electricity bill functioned as a boundary object. My analysis focuses particularly on the questions articulated by students as "perspectives" they take on a context that is largely unfamiliar to them. These serve as preliminary descriptions that will form part of a broader, ongoing activity-theoretic analysis of the mathematical modelling camp as a whole.

THEORETICAL FRAMEWORKS

Activity Theory

Cultural-Historical Activity Theory (CHAT) is a cross-disciplinary framework that conceptualizes individual actions as being meaningful only as part of a larger collective activity system. This tradition traces its roots to the work of Vygotsky and Leont'ev. CHAT maps actions and the sociocultural context onto an activity system composed of acting subjects, their shared object, the tools or artifacts utilized, and the factors that define the social configuration of the collective group. Under CHAT, this system or a network of such systems forms an irreducible unit of analysis. (Engeström, 2000)

CHAT has been adapted as a theory of learning by many scholars. In particular, the third generation of CHAT, as elucidated by Engeström, considers two or more activity systems that intersect in their object (goals), though not entirely. For this study, CHAT provides a schema to describe the different sociocultural worlds that share "boundaries," so to speak.

Boundary Objects

Star and Griesemer (1989) coined the term "boundary objects" to describe artifacts—such as biological specimen records—which connect and translate between various disciplines. According to the these objects "inhabit several intersecting social worlds and satisfy the informational requirements of each of them." The concept of a boundary object was subsequently appropriated by studies regarding boundary crossing. In certain discussions of CHAT and expansive learning, boundary objects can take on a much broader and more abstract meaning, which can include certain community practices. (Akkerman & Bakker, 2011)

In this study, the original conception of a concrete artifact that mediates communication between different social worlds is more appropriate for describing electricity bills. Thus, I will use activity systems to characterize the sociocultural worlds and the boundary object to describe how they intersect. Note that in this report, the activity systems intersect through the artifact used (the electricity bill) rather than through the "object" in the formal activity-theoretic sense. In the representation of an activity system as the mediational triangle, then these activity systems are loosely connected to each other at the top by the boundary object.

BACKGROUND AND CONTEXT

The study was conducted as an after-school program with sixteen Grade 9 students (8 boys and 8 girls) from a suburban area in Mumbai, India. The school was funded by a government body and provided a very high quality of instruction relative to the rest of the country and Mumbai.

This engagement was conceived and advertised as a mathematical modeling “camp,” consisting of a series of six two-hour sessions. During these sessions, students learned mathematical modeling within the context of household electricity. Students worked in groups on inquiry-driven activities that culminated in each group selecting and answering a question of their choice about household electricity that required mathematical modelling.

The participating students were recruited by asking four schools in the same neighborhood to nominate four students each to join the camp. Presumably, this selection process favored students with high academic performance and interest. Apart from this nomination, the camp was wholly independent of their school activities and assessments. The medium of interaction was primarily English, with occasional Hindi spoken. The camp sessions were conducted by me as the researcher-facilitator, supported by two members of the research team.

The exemplar electricity bill used for this activity were a real bill from a house in the same area, supplied by the same power company. Thus, the bill was simila to those received in the participants’ homes in both format and electricity rates. An activity was designed to familiarize students with the bill and to encourage them to observe patterns. This was implemented through a worksheet that guided their inquiry. The questions were designed either to assess their prior knowledge of quantities and units or to direct their attention to different sections of the bill without providing any external explanations. At the end of the worksheet, open-ended prompts elicited their observations, the thoughts that occurred to them during the exploration, and any questions they may have had.

METHODS

Data Collection

The camp sessions were audio- and video-recorded. Additionally, student work such as completed worksheets and other inscriptions was collected. Informed written consent was obtained from the parent or guardian of each participant regarding the recordings. The study design was reviewed and approved by the Institutional Review Board (IRB).

This report primarily comprises an analysis of data from the first two of the six sessions, which focused on the exploration of the electricity bill.

Analytical Approach

I adopt a qualitative interpretivist approach to elaborate on the role of electricity bills as boundary objects. The questions that students raised or articulated—both in writing and verbally—were identified and categorized. These questions were interpreted across two distinct activity systems: (a) the process of parsing the bill within an environment encouraging mathematical reasoning, and (b) the supply of electricity distribution and sale. For the sake of brevity, an analysis of two such student questions is presented here. Implications were drawn regarding the potential for contextual learning about the sale and distribution of electricity in general and its relation to the individual consumer.

ANALYSIS

Electricity Bill as Boundary Object

It must first be recognized that an electricity bill is a boundary object linking the power distribution supply chain and the consumer. Hence, the exemplar bill is highly detailed and contains information ranging from consumer identifiers and payable bill amounts to multiple payment methods and advertisements. These advertisements included promotions from the state government as well as consumer goods produced by sister companies of the power utility.

Within these two dense A4 pages, there are four sections that are of particular interest here: (a) a table deriving the number of billed electrical units (kWh) from meter readings; (b) an electricity tariff schedule containing all relevant charges and rates levied based on the billed units; (c) a table detailing the breakdown of specific charges for the current bill; and (d) a bar chart showing the monthly consumption pattern of the household for the twelve months prior to the bill. I will unpack sections (a) and (b) in the following sections.

The vast majority of this information is ignored by the average consumer. The two details that are practically relevant are the payable amount and the due date. The detailed breakdown of how the payable amount is calculated exists for the sake of transparency on the part of the power supplier and is enforced by regulatory bodies. However, a consumer knowing specific rates does not necessarily help them, as they

are beholden to pay whatever they are charged, especially in areas where there is no competing supplier.

On the other hand, almost half of the items in the detailed breakdown of the exemplar bill did not impact the final amount; that is, they were zero. Some of these charges are described using terms such as “Regulatory Asset Charges,” “Wheeling Charges,” and “Moratorium Amount.” Most are jargon from the economics of power distribution that often alienate the typical consumer. Understanding these terms does not grant more agency to the consumer. This resultant obfuscation also affected the participating students, who frequently became stuck on unfamiliar terminology. When asked what questions occurred to them after two hours of exploration, multiple students’ responses were, “What is a moratorium amount?” I posit that they inquired about it because it sounds exotic and/or esoteric, even though it does not contribute to the bill amount.

The electricity bill explored by the students was, in effect, significantly more opaque than transparent. The bill, as an information artifact, is designed to facilitate coordination within the power supply chain, a complex network of activity systems, rather than to serve the domestic consumer. The calculation of cost of electricity gets “black-boxed” (Williams and Wake, 2007) away from the consumer. The ability to parse an electricity bill is not solely dependent on numeracy or literacy; rather, it requires contextual knowledge far removed from both formal schooling and everyday life.

Boundary objects are rarely equally approachable from all worlds they intersect with. They are subject to political forces and often reinforce power structures. Thus, if one were to unpack mathematical relations or models embedded in a bill, one would encounter these structures wrapped within them. (Akkerman and Bakker, 2011)

“What is the Multiplication Factor?”

Figure 1: Bill section describing calculation for “Total Billed Units”

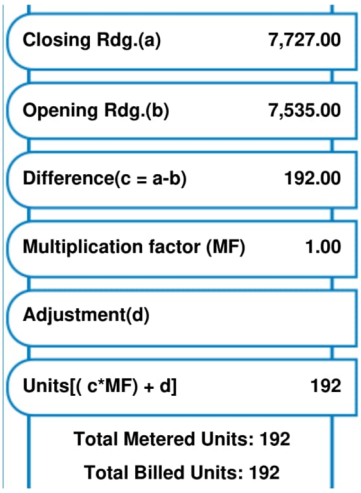

Figure 1 shows how the total billed units are derived from the closing and opening readings. It is interesting to note that the bill uses algebraic expressions to clarify the

procedure shown in the table. Every student who encountered this section could relay the procedure as a verbal instruction or expand upon it by describing the intermediate substitution. In this explication, they equated "Adjustment (d)" with zero, even though no figure was provided on the bill. Their school mathematics training enabled them to successfully parse this section.

After this exploration, multiple students asked, “What is the Multiplication Factor?” or “What is MF?” As they understood the underlying procedure, they realized it was “the factor by which one would multiply (c).” However, this cyclic explanation was not satisfactory to most, and the question was repeated. While the phrasing of their questions did not change, their tone and discomfort conveyed a frustration that I interpreted as, “What does it mean?” or “Why is it there?”

This tension was articulated in mathematical language by one student on their worksheet as: “What are adjustment and MF? Can they both be numbers other than 0 or 1?” (Paraphrased). In the next session, when the students compared multiple bills from different months, neighborhoods, and power suppliers, they noticed that these two factors remained constant at 0 and 1, respectively. When asked for their opinion on whether these values could be something other than 0 and 1, another student remarked, “They must be… or else why are they there?”

These observations and exchanges demonstrate a type of reasoning akin to a mathematical convention: “If it is named, it must be a variable.” This logic is made even more stark by the fact that these values leave the input “c” unmodified. The distinction made—listing metered units separately from billed units—suggests they should differ in meaning, even if they do not currently differ in value.

These two numbers correspond to processes that occur in exceptional cases: (i) an adjustment occurs if a meter is inaccessible for a particular billing period; in such cases, the consumer is charged based on the average of the previous three months’ usage, with any excess or deficit adjusted later; and (ii) the multiplication factor can be greater than 1 (for example, 1.5 or 2) if the connection draws a load in excess of what was sanctioned, acting as a penalty. These factors are not explained on the bill at all.

The algebraic explanations are supposed to help parse this section but a lack of explanation of the terms obfuscate it. Students were convinced that these factors must vary solely because they were mentioned though they never saw the numbers change across multiple bills.

"How are electricity tariffs calculated?"

Figure 2: Bill section describing "Electricity Tariff Schedule" applicable to the most common type of domestic electricity connection

ELECTRICITY TARIFF SCHEDULE

LT I (B) :LT-RESIDENTIAL	Energy Charges (₹ /kwh)	RA Charges (₹ /kwh)	CSS Charges (₹ /kwh)	Wheeling Charges (₹ /kwh)	Fixed/ Demand Charges(₹)	ED %	TOSE (₹ /kwh)
000-100 Units	2.18	0.00	0.00	3.15	90.00	16.00	0.2604
101-300 Units	5.36	0.00	0.00	3.15	135.00	16.00	0.2604
301-500 Units	11.62	0.00	0.00	3.15	135.00	16.00	0.2604
Above 500	12.56	0.00	0.00	3.15	160.00	16.00	0.2604

1) Residential (3 Phase) : Addl. Fixed charges of 160/10 kW or part thereof above 10kW shall be payable. 2) Electricity Duty as per G.O.M Notification No. ELD 2016/CR 252/ENERGY-1 of 31.10.16. 3) Tax on Sale of electricity as per G.O.M Notification No. VVK-2018/CR-161/Energy-1 of 26-12-18.

The payable bill amount is calculated based on the electrical units consumed and the various rates listed within a tiered or "slab-based" structure (see Figure 2). In simplified terms, the electrical units consumed are initially charged according to the lowest tier (0–100 units) until the usage exceeds 100 units. All subsequent units are then charged based on the rates in the second tier (101–300 units) ans so on. This calculation procedure is not explicitly explained on the bill.

During the bill exploration activity, several questions directed the students' attention toward the electricity tariff schedule. They were asked to notice differences in the units for various charges, distinguishing between charges rated by units consumed and fixed charges. Three students asked questions on their worksheets about the tariff structure or how the total bill amount is calculated. The question "How is the bill amount calculated?" was also raised during the discussion at the end of the session. As the facilitator, I prompted them to try figuring it out on their own. As I was closing the session, the following exchange occurred:

Student 1: I have a doubt here. So, on the backside (unintelligible) …on the right top corner there are bill details. In that, the energy charges amount to seven hundred and eleven (711). But when we calculated it should be around one thousand [twenty eight] (1028).

Student 2: [twenty eight]

Facilitator: What did you do to get one thousand twenty eight?

Student 2: Multiplied 192 by 5.36.

These two students had tried to see if the tariff table and bill details were consistent through calculation. Their initial understanding was that if monthly consumption fell into a certain tier, the entire consumption would be charged based on that tier, rather than through the progressive structure described earlier (e.g., 100×2.18+92×5.36). I prompted them to figure out the reason for this discrepancy.

By the next session, two other students were able to decipher the tiered calculation and managed to explain it to their peers. Once Student 1 understood the procedure, she

asked, “Why do we do it this way?” Depending on the context, her question meant either, “Why are charges calculated using this progressive tiered structure?” or “Why are there tiers at all?” Through the use of various mathematical tools and skills, the students were not only able to reverse-engineer the bill calculation procedure but also noted its inherent complexity. They did not understand the justification for this complexity, which stood out as an anomaly to a few students. Ultimately, the students were unable to pursue this question during the course of the camp, as they moved on to other activities.

DISCUSSIONS

The electricity bill was an almost completely unfamiliar artifact for the students, as their participation in household management was peripheral; most had not even seen their own household’s electricity bill at the start of the camp. However, through their own mathematical reasoning and skills, they were able to integrate it into the activity system of the mathematical modeling camp. Their actions were guided by mathematical principles such as compactness, consistency, and computational exploration. This led them to ask questions about a sociocultural world of which they were not a part. Although a full "boundary crossing" did not occur, these episodes demonstrate that such a crossing is potentially possible. How to support this crossing beyond this point, as well as exploring other mathematically rich boundary objects that can bridge disparate social “worlds,” remains a subject for future study. The ongoing analysis of this intervention aims to characterize how the electricity bill and household electricity evolved as mediating artifacts as the activity system of the camp itself developed.

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