Research Article

The Case of the Occasionally Cheap Computer: Low-cost Devices and Classrooms in the Developing World

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Abstract

The quest for the low-cost computer has been one of the most significant pursuits of ICTD since the 1990s. This article examines the experiences of low-cost computing projects in developing regions and looks at some of the common entrepreneurial and technical problems faced by past and current initiatives. Focusing specifically on the domain of education, we look at the quest for low-cost devices and consider their economic and socio-cultural appropriateness to the typical classroom in the developing world. Using field studies and interviews conducted in rural Indian classrooms, we show that shared rather than single-user devices constitute a more realistic and sustainable approach for low-cost computing projects targeting children's education.

I. Introduction

The past decade has seen a number of attempts to develop low-cost computers as a means of greater access to technology for underserved populations. Such projects have employed a range of strategies at designing interfaces and infrastructure differently to serve the unique needs of developing regions and populations with limited technology and textual literacy experience. At the same time, the devices themselves are designed as inexpensively as possible. However, most projects have fared poorly in markets, despite the apparent enthusiasm for many such initiatives. In this research, we look at a number of projects in the low-cost computing domain and examine them through the frame of how technology is designed and used in classrooms in the developing world. As our empirical base, we use research from our several years working with schools using computer centers that indicated a salient point: the most striking shortcoming, when considering technology in the classroom, has been the single-user model of computer use. As the starting point of our argument, we introduce evidence that computers tend to be shared by children throughout the developing world and present further evidence that this sharing is not just one of economic need, but is strongly embedded in cultural approaches to learning and asset use.

Our argument here is divided broadly into three parts and looks primarily at computer use for young children. First, we discuss briefly the reasons behind the recent boom in thought about technology and development and look specifically at major initiatives in the *Computers for the Poor* domain. We also take a detailed look at some of the practical rea-

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sons why some of these initiatives, despite their innovation and technological sturdiness, have failed and at what newer initiatives may be doing differently. Second, we look at sharing of computers, specifically at prevalent trends in classrooms of the developing world, especially in India where a bulk of this research has been done. Finally, after looking at the economics of sharing versus single-device models of technology, we turn to the mechanics of sharing to examine whether this offers any realistic learning games worth pursuing as a serious, practical option for computing.

II. Background

Before we look at the specifics of why computers in schools for the developing world are at the center stage of contemporary development discourse, we turn briefly to the recent history of development, specifically at the perceived role of technology in growth. We believe that several of the key macro- and micro-economic propositions on the value of technology in engineering growth have contributed to a rise in interest from engineering, industry, and philanthropy in developing low-cost computers.

A. IT and Development

The relationship between technology and development has been a consistent theme in social sciences. At a macro-economic level, the high-tech industry has been cast as an important engine for regional growth, while, at a micro-economic level, computers have been linked with human development. The academic community has been interested in the macro-economic aspect of this relationship since the 1960s with the emergence of a large body of literature that explored the knowledge economy (Machlup, 1962), especially in Japan, where work on Knowledge Society studies had emerged as a major field around the time of its gaining competitiveness in the global economy (Masuda, 1981). By the late 1970s and 1980s, this interest had taken on the hue of popular literature on post-Industrial economies (Bell, 1976; Gouldner, 1979) and a broader body of knowledge on Information Society theory (Duff, 2000). In the 1990s, the birth and rather rapid explosion of the Internet renewed interest in the idea of a changing world across scholarly and industry lines, in large part due to the interest of important thinkers from all sides of the spectrum (Castells, 1996; Negroponte, 1996), including, importantly, by a number of international development agencies (Hanna, 1994; Wehn & Mansell, 1998; Nulens & Van Audenhove, 1999; Gaiha, 2001). In addition to this idea of technology as a potential means of furthering development being fairly well represented, the work of management gurus like C. K. Prahalad on the bottom of the pyramid markets (Prahalad & Hammond, 2002) suggested that technology and development may not just be of interest to philanthropy or government, but may indeed have profit-making consequences for companies that choose to develop products for an untapped market further down the value chain.

While the late 1990s had already seen a few initiatives in technology for low-income regions, we argue that it was a burst of interest among engineers and scientists in issues of technology in the developing world that created a significant push and a subsequent slew of projects in this arena. This increase in interest started in the early 2000s with several leading academics from key universities forming small research groups and publishing works in the general area of technological innovation for the needs of the developing world (Parikh, Ghosh et al., 2003; Bhagwat, Raman et al., 2004; Pentland, Fletcher et al., 2004; Brewer, Demmer et al., 2005). In addition, concrete international research partnerships in technology and development emerged, a notable example being MIT's Media Lab Asia, which set up shop in India. Also around this time, research wings in major technology groups, including Hewlett Packard Labs and Microsoft Research, set up establishments in the developing world, which naturally prompted thinking about application ideas relevant to the needs of these markets, adding even further momentum.

B. Inexpensive Computing Devices

Historically, there have been numerous initiatives targeting the creation of "computers for the poor," but the quest for such devices has been an elusive one (see Table 1 for a selection). Arguably, the original "low-cost PC" was IBM's PCjr, which was launched in 1983 with much fanfare, including a magazine devoted to coverage of it even before its actual release. The product led to a wave of clones, some fairly successful, including the Tandy 1000, though it did not itself succeed in the market due to design issues. This first low-cost computer was not intended as a "computer for the poor," but was instead an attempt to extend the range of people having access to computers—in this case, from busi-

Table 1. Selected low-cost computing initiatives: Comparison of costs and current status of implementation.

Initiative	Usage Model	Envisioned Cost (US$)	Actual Cost (US$)	Targeted Users	Buyer	Status in 2007	Design Strategy
Simputer	Single user, sharable	$100	$200	Low-income users	Institutions, Individuals	Discontd.	Complete redesign, PDA form factor
OLPC	Single user	$100	$135 ($208)[1]	Low income children	Govt. / state	In prodn.	Complete redesign, small laptop form factor
Classmate	Single user	$400	$200+	Children	Individuals	In prodn.	Complete redesign, small laptop form factor
Computador Popular	Shared	$300	—	Kiosks	Individuals, subsidized	Never produced	Stripped-down desktop PC
NComputing	Shared—Thin Client	$11 / access terminal[2]	$66 / access terminal[2]	Classrooms Kiosks	Individuals	In prodn.	Server w/ multiple thin clients
HP 441	Shared	$250	$250	Classrooms Kiosks	Institutions	Discontd.	Server w/ multiple dumb terminals

1. While the estimated price for future sales is around $135, the actual cost of ownership (including maintenance) agreed upon in the MoU between OLPC and Libya was $208 per unit.
2. Excludes monitor.

nesses to home users—by drastically reducing device costs.

The second wave of low-cost PCs came in the early days of the World Wide Web. Products such as the Net PC were conceptualized (Russel, 1997), but never made it to widespread production, because the 1990s saw such rapid decline in PC prices that a low enough threshold for a "computer for the poor," as then imagined, could be attained by the market without any need to innovate. Back then, a $500 computer seemed like a quantum leap (Neugass, 1996), and most attention on the cost-minimizing side was directed toward optimizing the thin client architecture (Gaw, Marsh et al., 1998). This was, in some sense, understandable because of the dramatic drop in computer prices through most of that period. Yet the computer industry remained profitable due, quite simply, to the increase in the number of families in the developed world that annually became new consumers of home computers through this period (Bresnahan & Malerba, 1999). We argue that, on the business side, it was partly the normalization of demand through the developed world that expanded the interest of major companies in developing products for emerging markets. We also contend that a complementary argument for the rise in thinking around low-cost PCs tailored for the developing world came with the liberalization of several economies around the globe, where major PC manufacturers found strong competition from local non-branded PC assemblers (Dedrick, Kraemer et al., 2001).

This new wave of devices aimed to concurrently deal with what we see as three related, but sufficiently separate issues. The first, and most emphasized, was the reduction of the device cost. The second was the creation of form factors and functionalities specific to usage in developing countries, accounting for the lack of urbanization and infrastructure. This second factor was, at times, equated with building robust machines that withstood harsh weather, dust, and poor quality power, often gleaning inspiration from wearable computers for combat situations (Zieniewicz, Johnson et al., 2002). The third factor was that of "usage appropriateness," including issues related to literacy, cultural appropriateness, and social norms of resource sharing.

The pioneer in this most recent wave was the Simputer project that originated in 1998. The Simputer, or "Simple Inexpensive Multilingual Computer," (Chandru, Deshpande et al., 2001) aimed to address these three sets of issues. The device was sold at a considerably lower price point of US$200 compared to the average computer cost of US$1,000 on the market at the time, even though it was originally envisioned to cost as little as US$100. The Simputer attempted to work across the range of issues in building for developing regions: it had a damage-resistant casing; a plastic cover for dusty and hot weather; large, sturdy buttons for rough use; and an entirely new visual and input interface. The Simputer group put a significant effort into developing an intuitive UI with an OS interface designed with the needs of users new to technology and textual interfaces in mind. The Simputer featured icon-based screens and speech synthesis capability and was intended to be easily shared, with an individual flash card for each user.

The Simputer did not do very well in the market, for reasons we discuss later, but another project, with a somewhat orthogonal strategy toward providing low-cost computers, was taking shape in Brazil around the same time. Both projects came from academia in respective countries and were built with a Linux backbone to reduce the cost of the OS. Unlike the Simputer, the Computador Popular (CP) had very little device-level innovation. In fact, the CP was nothing more than a plain, stripped-down version of a PC running Linux, but the project was more important for a different reason: it was the first project within the ICTD space to actively seek government intervention to subsidize the cost of personal computers through reduced taxes and loans. This device was to be priced at US$300.

By the turn of the millennium, there was a burst of projects in this same arena for a number of reasons (cited above) as reflected in the entry of big tech companies into this space (Collins, 2007). Arguably, many of these tech companies departed slightly from their core businesses and competencies to try their hand at selling new devices in new markets, often with the unusual business model of designing products meant for markets that could not buy the products themselves. Instead, they had to be sold through institutional buyers, such as governments, philanthropies, or international agencies. Oracle had a brief brush with the "New Internet Computer" (started around 2000 and abandoned around 2003), which was priced roughly at US$199. Chip manufacturer Via Technologies designed a low-cost box-PC similar to the

AMD PIC[1] at a price point of approximately US$250. Intel, AMD's chief competitor, had its Community PC project and Classmate,[2] along with a collaborative project in China called the Beijing Rural PC. HP experimented with the 441 device, with a changed Linux kernel to support four keyboards and screens from a single processor, and priced at approximately US$1,200 for the entire unit. This attempt was abandoned, along with its parent e-inclusion program, in 2005, although the technology has lived on in products such as the "Useful Desktop Multiplier." Recently, NComputing released the X300 that uses low-cost access terminals connected over Ethernet to share a single PC with up to seven users, eventually hitting a price point of US$200 for three users, excluding monitors and peripherals. A quick survey of ICTD projects[3] shows that over 50 projects in the past 10 years have attempted to create low-cost computers for developing regions, a large chunk of them small companies assembling PCs in the BRIC nations, featuring brands like Fulong Mini-PC,[4] and E-DUC,[5] Sirius,[6] and SofComp,[7] as well as more rugged products such as the SuperGenius Bharat PC, which, like the AMD-PIC, was built to withstand rough use. An unlikely constituent of the low-cost PC market was the NGO world, with a number of experiments like the pedal-powered Jhai PC[8] and social entrepreneurship ventures like Inveneo[9] that again straddled the space between being outright market products and external funding-dependent development projects.

Probably the most discussed project, and arguably the one with the largest expectations, is the One Laptop Per Child (OLPC) initiative. Also originally known as the $100 laptop, or more recently the XO-1, the current price of the device is about US$208, but is expected to decrease with volume. This device, the brainchild of some of the leading scientists of the MIT Media Labs, is an inexpensive, low-power laptop designed for harsh conditions in developing countries and intended for distribution to children around the developing world. In many ways, the OLPC has come to exemplify the inexpensive computer space, but not just because of its charismatic promoter, Nicholas Negroponte, and the history of the Media Lab behind it. Much of the media attention focused on the project, plus its high-profile approach (of negotiating sales primarily with heads of government), made it somewhat of an exemplar of a project within the ICTD space. The OLPC project was in the news for impressive technological innovation as much as for its approach of recommending individualized laptops as a means of better learning for children in the poorest parts of the world, a position that was sometimes at odds with some of the most influential commentators in this area, including Bill Gates himself (Kraemer, Dedrick, et al., 2007). The idea behind the OLPC simultaneously raised hopes and criticisms; partner organizations frequently came and went (both Intel and Microsoft have, at different times, been supporters and opponents), and their participation frequently raised eyebrows.

C. The Occasionally Cheap Computer

While the complete fate of the computing-for-the-poor projects like OLPC remains to be seen, valuable lessons can be learned from the market experience of other similar projects in the past, which, unfortunately, were either entirely ineffective or enjoyed very limited success. Most such projects remained occasionally inexpensive at best, often moving swiftly from being inexpensive computers to abandoned projects, or to computers that could barely be considered cheap. The reasons for these outcomes were related to both the *supply* and the *demand* side of the market.

On the supply side, several of the companies producing these low-cost devices were either not typical computer companies (e.g., the Simputer, CP), or they were somewhat outside of their core competencies (e.g., Intel, HP, AMD) in terms of *production* for the former category, and *marketing* for the latter. In terms of production, these new devices could not promise large enough volumes at the produc-

1. *http://50x15.amd.com/en-us/*
2. *http://www.classmatepc.com/*
3. *Low-cost computing devices and initiatives for the developing world http://www.infodev.org/en/Publication.107.html*
4. *http://www.lemote.com/*
5. *http://www.e-duc.com/*
6. *http://www.fiveriverstech.com/sirius.htm*
7. *http://www.ncoretech.com/mobilis/index.html*
8. *http://www.jhai.org/jhai_remoteIT.htm*
9. *http://www.inveneo.org/*

tion end for their costs to be significantly competitive. Cost considerations also prevented device customization, and constrained manufacturers to building a single version of a device, rather than a suite of products. For example, you can buy only one configuration of the OLPC, two versions of the Simputer, one of the Classmate, and so on. Such products are difficult to sell to institutional buyers such as schools that are less inclined toward experimentation with untested products. On the marketing side, a fairly common approach of projects in the cheap computing space has been to emphasize the social relevance of computers to the poor, thus making a case for the government to underwrite the cost of these projects—either directly by being the buyer or indirectly through tax concessions. This has been a risky strategy that has rarely worked well due to a range of factors: state priorities in developing countries tend to be focused toward more basic spending; political stability (the OLPC, in particular, has suffered the flip-flopping of states on purchase commitments); equity (thus the problem of selecting the recipient group of free computers, assuming "everyone" would rarely be provided for); and, finally, procurement processes. Finally, on the distribution side, working through the government is detrimental in that it separates producers from the micro-environment within which technology sales and maintenance take place, such as training of local suppliers and support staff.

On the demand side of the market, the problems were even more challenging. Some design decisions, while optimized for a certain group of users, could end up defeating a product's appeal for a general audience, especially when some such designs are hard-coded into a device. This was the case with features of the Simputer and perhaps the keyboards of the OLPC or Classmate, which are quite optimal for young children, but a difficult sell for adults or other potential buyers of the otherwise powerful devices. A major concern for these devices when the entire computing paradigm is redesigned has been planning for the creation of appropriate content and applications. The Simputer, with its custom OS and interface, was especially affected by this, as getting a critical mass of developers working on creating applications for it depended on its widespread usage—a chicken and egg conundrum. Likewise, while constructivist learning arguments guided design arguments for a new OS and interface for OLPC, the approach exposes the device to the same risks as Simputer, of not having enough developers creating new applications for generic use on the device. This led to a larger "lack of things to do" problem for these devices, an issue ironically found to be a problem for another strand of ICTD projects—the community computer kiosks (Keniston, 2002). Designing applications for adults that do not have a conscious need for computers in their daily lives is non-trivial, as it is difficult to convince these adults to incorporate technology in possibly disruptive ways into their livelihoods (Nedevschi, Patra et al., 2006).

From the free market perspective, the "computer for the poor" faced its strongest challenge from standard low-end desktop computers. Below the US$250 mark, there is a whole range of Linux-based desktop products available both in the U.S. (e.g., Lindows Family PC), as well as several developing countries (e.g., ApnaPC). However, the largest challenger has been the neighborhood PC assembler, who puts together a computer with parts purchased off the shelf and shows up at the doorstep to fix things when stuff stops working. This segment offered machines with the same form factor and capability as a typical branded PC. That most low-cost PCs opted for Linux-based interfaces was an obvious cost-cutting approach that again turned out to be a competitive disadvantage against smaller assemblers in the informal market that could afford to throw in a hot copy of the much-desired Windows OS for no additional cost. In all, the real cost advantage offered by most low-cost computers was very small. Finally, an unanticipated demerit of the low-cost computing machine may have precisely been its branding as a low-cost device. Research showed that the association of ICTD products with low-income groups or low-attainment populations had a damaging brand impact, because the target market perceives purchasing "computers for the poor" as a climb-down of status (Ferraz, 2004). Some similar findings have also been observed in user attitudes toward subsidized community computer centers (Kuriyan, Toyama, et al., 2006).

D. Computers and Children's Education

We turn now to the specific argument on many an investment plate for the use of low-cost computers by children in classrooms of the developing world. Frequently, this is the first intended market of such initiatives, often engraved with brand names, as in the cases of OLPC and Classmate. In developing regions, we see two major reasons for the focus of computer projects on children within the environment of a broader developmental focus toward sustainability and human development investment. The first reason has been the shortage of existing trained teachers, thus shifting the emphasis toward what can be done independent of the systemic shortcomings. The relative importance of this is evident in the structuring not just of the low-cost computer projects, but also in some of the more recent applications of technology toward learning in the ICTD space, such as language acquisition using technology that has been designed to largely eliminate the teacher and allow for greater independent interaction between the child and the system (Kam, Ramachandran, et al., 2007). A second factor has been an increase in interest in constructivist approaches to learning that have influenced not just the building of devices, as in the case of the OLPC, or for that matter, historically, in a number of past projects on children and learning (Papert, 1993), but also in the structuring of technology projects for children more broadly (Baggio, 2000).

In addition to these factors specific to computers and children, the wave of increasing investment in ICTD projects created a number of shared technology centers offering public access to computers, a number of which were co-located in schools (Proenza & Montero, 2001; Colle, 2005). Some of the low-cost computing products such as the HP 441 were specifically designed for use by multiple users in school classrooms or telecenters. NComputing's X300 was designed as a thin client solution for building school computer labs, and the VIA low-cost PC was also envisioned originally for classrooms. The Simputer featured a number of children's applications in its original design, but was intended to be shared, not in simultaneous sessions, but passed along from one child to another in turns. Though made for classrooms, the Classmate and OLPC were not intended as shared devices; instead, they were to be used as take-home computers with which children explored learning techniques. No broad estimates are published on the extent of access to computers in schools in the developing world, but both computer centers and individual computer purchases are on the overall rise. In the case of the OLPC, it has been reported that at least 15 unbinding purchase discussions with countries, including Nigeria, Libya, and Rwanda, have occurred, but it is unclear how many actual purchases have been made. The OLPC approach of selling in huge quantities (orders for one million or more pieces) is good for cost reduction, but seems to be better suited for countries with a comparatively more centralized decision-making process on large state purchases. In India, for instance, the idea of OLPCs in classrooms was rejected with the argument that "it would be impossible to justify an expenditure of this scale on a debatable scheme when public funds continue to be in inadequate supply for well-established needs" (Mukul, 2006).

This leads to a larger question, given the thrust of spending on technology for classes: Can computers actually complement teachers and make learning more valuable? This question is actually far from settled as there is very little consensus on what the benefits of technology in classrooms are and even less consensus on the comparative benefits of computers versus other kinds of interventions. While studies show that children's access to computers yields clear gains in certain types of skill building (Attewell & Battle, 1999), especially when these are home computers, there is an abundance of material to suggest that the context within which the computers are used is critical to ensuring both education efficiency and equity in education opportunity. There is strong evidence that investment in computers can be highly inefficient (Cuban, 2001), particularly when it is driven by an enthusiasm for technology rather than the needs of the children. There is also evidence that the positive impact of access to and use of computing facilities can be highly biased (Becker, 2000) due to cultural and cognitive factors.

III. Approaches to Classroom Computing: Usage Models and Economics

We seek to address here the rather provocative question of how computers should be used in primary school classrooms from a supply perspective. We consider the devices and the means of using them, not the larger issues of what specific learning end goals computers work stronger toward. We turn thus to shared computing, which is central to our argument from this point on. Part of the goal of looking at past initiatives targeting computers for children was not only to understand what they did wrong from a market perspective, but also to understand how well these projects fit with the practicalities of computer use in classrooms. Moving

Figure 1. A single-child usage scenario for OLPCs in Iraq. (© Wikimedia Commons)

Figure 2. A typical shared computer lab for middle school children in India.

on, we find that the single biggest missing factor that perhaps explains why computers in the classroom of the developing world have borne the burden of looking gimmicky has probably been the lack of attention to sharing. In our collective experience from India, South Africa, Rwanda, and Brazil, the one constant feature of computer centers in poor primary schools has been that computers were shared among multiple users, anywhere between two and 10 children per PC. We propose a few shared- and single-use models of computer use to look at some of the merits and disadvantages of both.

A. Usage Models

We distinguish here between three models of computer usage for child education: single ownership (Figure 1), single user per classroom computer/terminal (Figure 2), and multiple users per shared classroom computer (Figure 3). More models are possible, and indeed, as we will note, some initiatives share properties with each model. We find these categories useful, however, for understanding the design decisions of specific initiatives and for demonstrating, in later sections, how the choice of usage model must match existing contexts and practices to have a long-term impact on establishing more equitable education. Given the comparatively greater portion of India-related research in this article, our sample has biases toward the specific conditions there, but our work in other countries leads us to believe that most of our findings resonate across conditions in other developing regions.

1. Single ownership: OLPC and Classmate: The OLPC and Classmate are both designed for single users, and while the Classmate is oriented to individual and institutional purchases, the OLPC was originally meant only to be purchased in quantities of one million-plus by governments. The recommended usage is individual child learning, parent-child collaboration, or teacher-child collaboration. The Simputer had a PDA form factor with a durable casing, and a few buttons designed for dust and head were also trying to target the same application domain. This device was also intended for individual use, but it was easily sharable, with pluggable flash memory cards for each user. Given these features, the Simputer could be passed from child to child, or from home to home, with each child or home responsible for its individual flash memory. This fact, as well as other design characteristics of the design (such as speech synthesis for illiterate users), points to some level of consideration for existing cultural practices and economic realities of the targeted user base. The OLPC probably presents a number of innovations on the interface front, including a smaller, flatter keyboard, a dual mode screen with low-power consumption, and white reflective sunlight to allow readability for open air conditions. However,

Figure 3. Shared computer using multiple mice. (Photo courtesy of Microsoft Research India)

both the OLPC and the Classmate are designed as take-home devices, and their small screens make them difficult to share without an externally connected screen.

2. Single user per community-owned computer/ terminal: A second usage model, which has been the standard in U.S. primary schools as well as some slightly better-off schools in the developing world, is the computer lab: a classroom dedicated to computer usage where each child has access to a computer in the classroom environment. In this model, the responsibility of purchasing and paying for computer maintenance is shared by the community. The teacher plays a primary role in educational settings that adopt this model, guiding and supervising child-computer interactions. The HP 441 was meant to share a single processor over multiple users, but only have a single user per terminal. NComputing's X300 was, likewise, designed to be shared by up to six individual users, each at a terminal with its own monitor and keyboard. Devices that target the usage model in which single users operate computers that are shared by the community tend to feature low-cost versions of standard PCs. The ownership by the community allows for higher prices per unit, but in practice, the cost is comparable to devices that target a single ownership model. Community-owned computers operate in a group setting, where group interactions external to the child-computer interaction play a central role in their overall use.

3. Multiple users per shared computer: In practice, there is no reason why the second mode of desktops in computer centers, as mentioned above, cannot be shared further by groups of children, and indeed, in most cases, this is how the computers are actually used. Products such as the HP 441 or X300 have the computing capability of a typical standalone PC. While not specifically marketed to multiple users per terminal, these devices could cater to groups of children huddled around each terminal as they'd been designed. In fact, space and power restrictions make it such that computers are most likely to be shared in simultaneous sessions, if they ever make it to a school in most parts of the developing world. Given this, we find that a striking missing factor is the lack of innovation in the "computers for the poor" space on efficient shared computing. One initiative, started by some of the authors of this article, looked at the use of multiple mice (on a single machine) to support up to five simultaneous students; this would require adding minimal peripheral spending and tinkering with the applications for better use across children (Pawar, Pal, et al., 2006). While this is clearly a restrictive format of interaction with a computer, we find that, for the unique needs of primary schoolers using devices for computer-aided learning, a mouse alone is usually enough, given that the typical "narrative-interactive" loop of practically all of children's learning software relies mostly on multiple choice click screens. That being said, the potential of multiple keyboard usage (Tse & Greenberg, 2004) and alternate text-entry, using mice or other devices, is both a possibility and an existing area of research. Further, we could also draw learnings in this area from some of the other projects, including the Simputer, to expand the use of flash memory to give each child profile individual memory for shared sessions. The intuitiveness of such usage models and screen sharing has been shown (Moed, Otto, et al., 2009), and there is already much precedent for screen use within the realm of multi-player video games (Nintendo, Playstation, etc.) that allow for the same variety of interaction modes (parallel, competitive, and collaborative).

Given what we know about the various models of technology use in classrooms and the prevalence of the shared-use model in actual practice, we need a clearer idea of how this could work in practice and what the major benefits or drawbacks of such a usage model would be. We approach this question by comparing shared-usage models with the two single-user scenarios, based on cost, educational effectiveness, and socio-cultural appropriateness of the shared model. For the two latter cases, we reference existing research on educational effectiveness of multiple-mice models and an interview-based study of socio-cultural attitudes toward device sharing in rural India.

IV. Economic Feasibility

In this section, we evaluate the economic feasibility of various computing initiatives for schools and their associated usage models. Given the harsh financial constraints, cost is one of the most important considerations for any of these initiatives. We consider both initial capital costs and running costs, including replacement, maintenance, and additional expenditures for developing appropriate content and training of teachers.

An economic analysis of the "computers for the poor" projects is necessary, because these projects have typically targeted government buyers, projecting the provision of computers to children as a state responsibility. The most important criticism of such projects, and often one very difficult to address, is the argument that money would be better spent on school buildings, safe drinking water and toilets in these schools, books, additional teachers and so on—all basic needs and with immediate returns on investment. In contrast, computers-in-education initiatives address less stringent needs and can only show a long-term return on investment. It is not our goal to claim here that the hierarchy of needs argument applies absolutely, and that investment in computers should be preceded by the solving of all other world problems. Governments all around the world are introducing computers in schools in moderation, attempting to balance these expenditures with more basic ones. However, it is essential to ensure that already scarce resources are utilized in the most effective way. It is notable that the two countries making the most progress in adopting OLPC-type programs are Libya and Nigeria, both nations with limited political opposition to getting them accepted at the highest levels.

A. Reduction of Computing Cost

Most low-cost computing initiatives are reducing the capital cost of hardware by riding on the computer industry's exponential trends of increasing integration and performance. They also downgrade or remove certain components from the final device. Such initiatives often use low-end processors (OLPC uses the AMD Geode, Classmate uses low-power Intel processors), replace hard disk with flash memory, and remove other capabilities like high-end graphics, optical drives, and peripheral connectors. The cost of ownership can be reduced by lowering the running cost of power. Power consumption can be reduced by using lower-power displays and smarter sleeping techniques. Interestingly, refurbished computers have performed poorly due both to maintenance and to disenchantment with "second rate" computers (Fonseca, 2004).

Though the overall cost of computing has gone down, none of the low-cost devices have broken the off-the-shelf US$200 mark (not including the cost of maintenance). OLPC's XO-1 laptop expects to achieve this by selling the hardware in batches of at least one million. However, according to the contract between OLPC and Libya, the cost per device, including maintenance, is US$208. Interestingly, Intel's Classmate PCs were initially sold at a price of US$400, but their price is expected to fall to around US$200 as well. The cost of NComputing's X300 is also expected to fall to US$11 per access terminal in large production volumes (Dukker, 2007).[10]

B. Cost Comparison

To compare the economic viability of various deployment models, we consider the capital and operational cost of providing computers in the whole of India. As discussed earlier in Section III, we consider three scenarios:

1. *Single ownership model.*
2. *Single user per community-owned computer/terminal:* We assume a ratio of one computer per 10 children in the school. During classes, each child gets his or her own computer.
3. *Multiple users:* We assume a ratio of one computer per 40 children. During computer classes, three to five children share a computer. This can be done with or without multiple input devices.

We use data about schoolchildren distribution in India from the Department of Education, Govt. of India (2008). Approximately 1.04 million schools in

10. *Dukker, S., & Bender, W. (2007). "Will Low-Cost Laptops Help Kids in Developing Countries?"* The Wall Street Journal, *5 September.*

Table 2. Parameters for cost comparison (budgeted on state school computers in India).

Cost of desktop PC that is shared	Rs 25000 or US$530
Cost of maintenance paid by Govt. for each PC (per year)	Rs 1800 or US$38
Cost of teacher (per year)	Rs 24000 or US$510
Cost of laptop (e.g., XO-1)	Rs 9770 or US$208

Table 3. Comparison of costs for various scenarios for deployment of computers in all rural schools of India (total of 165 million students in 1.04 million schools).

Metric	Scenario 1	Scenario 2	Scenario 3
No. of computers (million)	149.40	15.19	4.00
Total initial cost ($billion/year)	31.06	8.08	2.15
Cost of replacement ($billion/year)	6.21	1.62	0.43
Cost of maintenance ($billion/year)	5.72	0.58	0.15
Cost of teachers ($billion/year)	0.48	0.48	0.48
Total cost ($billion/year)	12.42	2.68	1.06

India serve about 165 million children between the ages of 6 and 13. The schools vary in size, serving less than 30 students to more than 300 students. Approximately 91% of all schools in India, and overwhelmingly so in rural India, are government-aided and/or managed schools (Ministry of Human Resources, Govt. of India, 2008). Infrastructure resources in these schools are very scarce: 59% of all Indian schools have no safe drinking water, 26% no blackboards, 89% no toilets, and less than a quarter of the schools have functional access to electricity (UNESCO, 2006).

Table 2 summarizes the cost parameters involved in our comparison, based on latest figures from OLPC and the Indian government. For scenarios (2 and 3) where desktop computers are used in classrooms, we use cost figures reported from current deployments of computers in Indian schools (including expenditures for teacher salaries and maintenance of equipment that the Government provides) and recent market prices for desktops. We assume a gradual deployment model where computers are introduced over five years. Assuming that the lifetime of the computers is also about five years, the replacement capital cost for the hardware every year is one-fifth of the total capital cost. We also assume that each school has only one computer teacher.

The cost comparison, showing the total cost per year for all the three scenarios, is presented in Table 3. As can be seen, the annual cost of providing shared computers (one per 40 children) to all of 165 million Indian students is only about US$1.06 billion a year. In contrast, the annual expenditure of providing laptops to every child is about 12 times higher at US$12.42 billion. These are conservative estimates that ignore the additional costs of running such a large program, such as costs associated with recurring power and other infrastructure needs in schools, with developing educational content in local languages, and with providing Internet connectivity to schools.

The total public expenditure for India on education was about US$22.9 billion (3.3% of GDP) in 2004, of which 30%, or US$6.8 billion, was allocated for primary schooling. In these conditions, it is unrealistic to expect the Indian government to spend more than half of the education budget on buying computers, especially without having any guarantees on the educational benefits of such a program.

V. Education Effectiveness

An important way to compare across usage models is by looking at the educational value provided by those models. The question of how to best define value would be better settled in open debate by education scientists. However, it is possible to compare across usage models by relying on studies with easily quantifiable metrics based on objectively assessable learning outcomes.

Few studies focus on learning outcomes in the single computer per student model. The OLPC project is starting field studies with the XO-1 project in a few countries. Maine's One Laptop per Child project (Muir, 2004) conducted some studies, but results did not find that a separate computer per child leads to strong and measurable changes in learning outcome metrics. However, for scenarios with computers inside the classroom, we present preliminary results from India for various single- and multi-user scenarios, using single or multiple input devices. We find that learning effectiveness with collaborative usage on multiple input computers can be as pronounced as learning with single-user computers in classrooms. This is a finding we attribute to the inherent social nature of learning provided in shared computing scenarios.

A. Study Methodology in India

We conducted observations and qualitative interviews during May 2005 and August 2006 at 22 schools in India, all catering to children from disadvantaged backgrounds. Selection of schools was based on regional profile and longevity of their computer-aided learning programs. These programs were state supported and contracted to Azim Premji Foundation, an NGO that sets up computer-aided learning centers for children. A total of 179 interviews were conducted with parents, teachers, various stakeholders in local education, and policy makers on their views about computers in schools, and the short- and long-term goals of their programs. We observed fifth and sixth grade children as they sat in front of computers and used the applications provided to them by the schools visited.

We tried two approaches to work toward the goal of providing equity to all users around the shared resource (the PC with the learning application): first, enforced resource sharing, and second, multiple input. Results published elsewhere (Pawar, Pal, et al., 2007) showed that, in the former case, there was often some degree of collaboration among children, especially as the "alpha children" (i.e., the typical mouse controllers and usually the scholastic achievers within groups) tended to discuss learning material with others in a group, leading to some impact on learning. However, in practice, this was a difficult goal to realize as the alpha children grew impatient with their role as surrogate teachers and wanted complete control for themselves.

Due to teacher shortages, children are often required to learn and manage how to use computers themselves with limited teacher intervention, making supervision-intensive tasks difficult. As a result, children who established dominance among their own small groups of colleagues tended to repeatedly be "mouse controllers" who dictated the pace of computer-aided learning sessions. Observations of eye contact with screens showed that mouse controllers were predominantly in command of the entire interaction and learning trickled down from them to other children. Thus, the main finding was that, with regard to computers in schools, even where equitable access was available, the dynamics of sharing among children often created new forms of power structures, generally to the detriment of the children who are most in need.

B. Experiments with Multiple Input Devices in India

Following our initial findings on device sharing, we tried using a single computer with multiple mice on test applications to see if there was any difference in children's learning in the new modality. Looking at the educational applications being used in the schools, we tested a word learning application in September 2006 with 238 children (11–12-year-olds) in various single- and multi-user scenarios, using single or multiple input devices. The children were shown a number of words that were new to them and then asked to identify the words from multiple choice options. The application used a game format and was tested in real classroom settings in rural India—two schools selected from among recently-instituted computer-aided learning programs.

Children were tested for a list of English words before and immediately after the test, and the words were included in the test application. Children were asked to play in four modes: (1) single-user, single input mode; (2) multi-user, single input mode; (3) multi-user, multi-input competitive mode; and (4) multi-user, multi-input collaborative mode. All multi-user modes had five users. The simple single-user, single-child mode (mode 1) is the model for which most applications are designed. Mode 2 is the closest to the typical usage scenario observed in India (and elsewhere) with many children at one computer, but only one controlling the

Table 4. Words learned during tests across single- and multiple-user shared-input modes (N =238, α = 0.5).

Mode	Word Gain	Engagement	Response Error	Decision making	Domination by single child
1	4.11	High, tails off	Low	Individual	n/a
2	3.77	Low	Very Low	Collaborative	Varied
3	3.60	Very high	High	Individual	None
4	4.30	High	Very Low	Collaborative	Varied

mouse. In mode 3, each child had a mouse, and the one who clicked the right answer first earned points. In mode 4, each child had a mouse, but the application moved to the next stage only if all children had identified the correct response.

During two rounds of experiments (Pawar, 2007) with a total of 238 children, we found that, for the specific application of word learning, children were able to consistently retain the most in mode 4 (see results in Table 4). The stark differences in results came when we looked at results separately by gender, and this emphasizes the social nature of learning, as gender influences social behavior and engagement which, in turn, affects learning. Overall, a key observation for this learning task was that multiple mice could offer the same benefits. In the competitive mode however, learning was hampered, as competition lead to a decrease in collaboration.

Hence, we found that increasing access to input was not sufficient in itself to make the learning more effective; collaboration was an essential part to improve the quality of learning. More detailed results from these tests are included in a work of greater exploration elsewhere (Pawar, 2007). The tests were used only to establish short-term retention. On the whole, they were useful in creating a case for collaborative learning over single display groupware (SDG), a case that has in the past also been made of mathematics (Bricker, 1995; Inkpen, 1995) and visual learning (Inkpen, 1999).

VI. Socio-Cultural Suitability

A common criticism of "computers for the poor" devices has been that they have not been grounded in good design principles (i.e., that look at devices contextually), but are designed in a lab-centric rather than need-oriented paradigm (Fonseca, 2006). Two important factors that need to be evaluated are whether the computer usage model under consideration is suitable in the actual social context and whether it would fit well with existing teaching methods in developing countries. Our goal is to work within the limitations of the current deployments that are already happening and work incrementally to increase access for all children.

Parents' beliefs about computers and education: Our primary research showed that both parents and teachers controlled the amount of time that children were allowed to work on computers in India, often very restrictively since the computer was the most expensive, or the only electronic gadget at home. As many as three years into having access to computers, teachers in some schools still let children use the computers only under their supervision. Likewise, many parents did not allow their children to use the television sets at home. The idea that parents, especially those in very poor families with no household assets, will allow and encourage use of computers in the same way as parents in developed countries may be a gross overestimation.

To dig deeper, we conducted interviews with 165 parents across four districts to determine parents' feelings about the use of computers in schools and homes. The interviews sampled a wide range of parents whose ages ranged from 24 to 70 and who had completed between 0 and 12 years of education. The interviews revealed an extremely important role played by parents in decisions about children's use of computers in schools: When asked if computers should be in schools, in the home, or both, parents overwhelmingly chose schools (Table 5). In other words, they disfavored the single ownership model adopted by OLPC and Intel Classmate. Most of them cited the primary role of teachers as their reason for preferring computers in schools.

Due to a system of education very centered on structured learning coming from the teachers to the students, parents were not convinced that games

Table 5. Parents' beliefs about computer usage models.

Reasoning	Preference for location of computer	Fraction of parents (%)
Cannot learn at home	School	31
Only teachers can teach	School	32
Children will learn better in collaboration	School	24
Don't want responsibility	School	8
Lack of power, etc., at home	School	4
Ease of access, device safety	Home	3

could have a positive role to play in children's learning. They were more concerned with ensuring children's progression through curriculum. Computers are generally seen in a positive light and beneficial to children, but mostly when working on them leads toward immediate better learning. For example, when asked if the same amount of money should be spent on teacher salaries or a new computer, 60% of parents felt that additional teachers would be a better investment for learning, whereas 40% thought that the one-time purchase of a computer would positively impact student learning.

Compatibility with existing teaching methods: We also found that early exposure to computers in developing countries comes through curricular content based on the dominant teaching methodologies, which tend to be highly structured and instructive rather than constructive. Almost universally, we found that computer-based learning material for children reflected the classroom: it is created in a "narrative-interactive" loop fashion, with the application feeding some content first, and then follows up with multiple choice-type questions that test a child's understanding of the material. We found this to be highly compatible with content on multi-input, single-screen computers.

The central role played by teachers in making such programs effective has been much discussed (Scott, 1992), as has the idea that class and cognitive issues impact the level and complexity of access that is available to children. Social class can also have an impact on computer learning: There is evidence that children from marginalized and underserved groups tend to do more drill-type activity, whereas children from affluent backgrounds tend to get greater access to higher-level activities and creative resources on computers (Means, 2001).

VII. Conclusion

Our reference to the "Occasionally Cheap Computer" is meant to underscore the dilemma of low-cost computing in the developing regions. Many initiatives in this space have attempted and succeeded in bringing down the cost of computing devices, and in the process have often brought about remarkable new breakthroughs that will benefit technological advancement on the whole. Yet the market experience of these projects has been poor overall so far, and many of the projects don't end up looking so cheap after all once they get in shape for distribution. Our argument here is that there is a need to take a step back and look at what the market seems to be telling us. We propose that an incremental approach to bringing technology to the classroom in the developing world is the direction to take ahead. Instead of building new devices that require both expensive R&D and a greater threshold of arguing for adoption, considering the institutional buying modes these projects operate in, it is far easier to work within the realm of "off-the-shelf" computers, as we propose here. The shared-computer use model that we propose here may not have the best case benefits of an ideal "laptops for all" scenario, but our argument is that it is not feasible to think of the former, and besides the core economic arguments, we have also provided learning gain potentials and parental attitudes toward shared-computer use to support our position. This approach to shared computing thus explores how we can best maximize the benefits of computers for children that are likely to be used in primary schools in the developing world and in small computer centers where children sit in groups. ■

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References

Attewell, P., & Battle, J. (1999). "Home Computers and School Performance." *The Information Society* 15(1): 1–10.

Baggio, R. (2000). "A Sociedade da Informação ea Infoexclusão." *Ciência da Informação* 29(2): 16–21.

Becker, H. J. (2000). "Who's wired and who's not: Children's access to and use of computer technology." *The Future of Children* 10(2): 44–75.

Bell, D. (1976). "The Coming of the Post-Industrial Society." *The Educational Forum* 40(4): 574–579.

Bhagwat, P., Raman, B. et al. (2004). "Turning 802.11 inside-out." *ACM SIGCOMM Computer Communication Review* 34(1): 33–38.

Bresnahan, T., & Malerba, F. (1999). "Industrial Dynamics and the Evolution of Firms' and Nations' Competitive Capabilities in the World Computer Industry." *Sources of Industrial Leadership: Studies of Seven Industries:* 79–132.

Brewer, E., Demmer, M., et al. (2005). "The case for technology in developing regions." *Computer* 38(6): 25–38.

Bricker, L., Inkpen, K., Stewart, J., Myers, B., et al. (1998). "Single Display Groupware: Exploring Computer Support for Co-Located Collaboration," Panel submitted at ACM SIGCHI'99, Pittsburgh.

Castells, M. (1996). *Rise of the Network Society.* Cambridge, MA, Oxford, UK: Blackwell Publishers.

Chandru, V., Deshpande, V. L., et al. (2001). *The Simputer: Radical Simplicity for Universal Access.* Development by Design: ThinkCycle Open Collaborative Conference, Bangalore 2002.

Colle, R. D. (2005). "Building ICT4D capacity in and by African universities.'" *International Journal of Education and Development using ICT* 1(1).

Collins, L. (2007). "Cutting the Cost of Computing." *Engineering & Technology* 2(2): 34–37.

Cuban, L. (2001). *Oversold and Underused: Computers in the Classroom,* Harvard University Press.

Dedrick, J., Kraemer, K. L., et al. (2001). "Impacts of Liberalization and Economic Integration on Mexico's Computer Sector." *INFORMATION SOCIETY* 17(2): 119–132.

Department of Education, Ministry of Human Resource Development, Government of India. (2008). *Statistics.* Retrieved March 1, 2008, http://www.education.nic.in/Elementary/elementary.asp

Duff, A. S. (2000). *Information Society Studies,* Routledge.

Ferraz, C., Fonseca, R., et al. (2004). *Computing for Social Inclusion in Brazil: A Study of the CDI and Other Initiatives.* First UCB-UNIDO Bridging the Divide Conference, 2004, Berkeley, CA.

Fonseca, R., & Pal, J. (2004). "Computing Devices for All: Creating and selling the low-cost computer." 1st International Conference on ICT and Development, Berkeley, CA. ACM IEEE Conference Proceedings.

Gaiha, R. (2001). "Decentralization and Poverty Alleviation in Developing Asia." *Economics and Development Resource Center,* Asian Development Bank, Manila. Processed.

Gaw, D., Marsh, A., et al. (1998). Low-Cost Multi-Service Home Gateway Creates New Business Opportunities, Coactive Networks, http://www.coactive.com

Gouldner, A. W. (1979). *The Future of Intellectuals and the Rise of the New Class: A Frame of Reference, Theses, Conjectures, Arguments, and an Historical Perspective on the Role of Intellectuals and Intelligentsia in the International Class Contest of the Modern Era,* Seabury.

Hanna, N. (1994). *Exploiting information technology for development: a case study of India,* The World Bank.

Inkpen, K. M., et al. (1999). "This is fun! We're all best friends and we're all playing: Supporting children's synchronous collaboration." International Society of the Learning Sciences.

Kam, M., Ramachandran, D., et al. (2007). "MILLEE: Mobile and Immersive Learning for Literacy in Emerging Economies." *TIER Research Group,* University of California at Berkeley.

Kraemer, K. L., Dedrick, J., et al. (2007). "One Laptop Per Child (OLPC): An Education Project or a Laptop Project?"

Kuriyan, R., Toyama, K., et al. (2006). "Integrating Social Development and Financial Sustainability: The Challenges of Rural Computer Kiosks in Kerala." *Information,Technologies and International Development 2006. ICTD'06. International* Conference: 121–130.

Machlup, F. (1962). *The Production and Distribution of Knowledge in the United States.* Princeton University Press.

Masuda, Y. (1981). *The Information Society as Postindustrial Society,* World Future Society.

Moed, A., Otto, O., et al. (2009). *Reducing Dominance Behavior in Multiple-Mouse Learning Activities.* 8th International Conference on Computer Supported Collaborative Learning (CSCL 2009)—Submitted, Rhodes, Greece.

Muir, M., Knezek, G., & Christensen, R. (2004). "The power of one-to-one: Early finding from the Maine Learning Technology Initiative." *Learning & Leading with Technology* 32(3): 6–11.

Nedevschi, S., Patra, R., et al. (2006). "A Multidisciplinary Approach to Studying Village Internet Kiosk Initiatives: The Case of Akshaya." E-Learning 3(3): 291–316.

Negroponte, N. (1996). *Being digital,* Random House Inc. New York.

Neugass, H. (1996). *The $500 Internet Computer.* 13th TRON Project International Symposium, Washington, DC. IEEE Computer Society.

Nulens, G., & Van Audenhove, L. (1999). "An Information Society in Africa?: An Analysis of the Information Society Policy of the World Bank, ITU and ECA." *International Communication Gazette* 61(6): 451.

Papert, S. (1993). *The children's machine: rethinking school in the age of the computer,* Basic Books, Inc. New York.

Parikh, T., Ghosh, K., et al. (2003). "Design studies for a financial management system for micro-credit groups in rural India." *Proceedings of the 2003 conference on Universal usability: 15–22*

Pawar, U. S., Pal, J., et al. (2006). "Multiple Mice for Computers in Education in Developing Countries." *International Conference on Information Technologies and Development, May 2006, IEEE Conference Proceedings.*

Pawar, U. S., Pal, J., et al. (2007). "Multiple mice for retention tasks in disadvantaged schools." *Proceedings of the SIGCHI conference on Human factors in computing systems:* 1581–1590.

Pawar, U., Pal, J., Gupta, R., & Toyama, K. (2007). "Multiple mice for retention tasks in disadvantaged schools." ACM SIGCHI'07 Conference Proceedings, pp. 1581–1590.

Pentland, A. S., Fletcher, R., et al. (2004). "DakNet: Rethinking Connectivity in Developing Nations."

Prahalad, C. K., & Hammond, A. (2002). "Serving the World's Poor, Profitably." *Harvard Business Review* 80(9): 48–57.

Proenza, F., & Montero, R. (2001). "Telecenters for socioeconomic and rural development." *Inter American Development Bank,* Working Papers.

Russel, J. (1997). "No End in Sight Over NC/NetPC Debate." *Communications Week.*

Tse, E., & Greenberg, S. (2004). *Rapidly prototyping Single Display Groupware through the SDGToolkit,* Australian Computer Society, Inc. Darlinghurst, Australia.

UNESCO Institute for Statistics (UIS). (2005). *Children out of school: Measuring exclusion from primary education.* Montreal: UIS.

Wehn, U., & Mansell, R. (1998). *Knowledge societies,* Published for and on behalf of the United Nations by Oxford University Press, New York.

Zieniewicz, M. J., Johnson, D. C., et al. (2002). "The Evolution of Army Wearable Computers." *IEEE PERVASIVE COMPUTING:* 30–40.