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Information and communication technology for development can greatly improve quality of life for the world's neediest people.

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How Computer Science Serves the Developing World

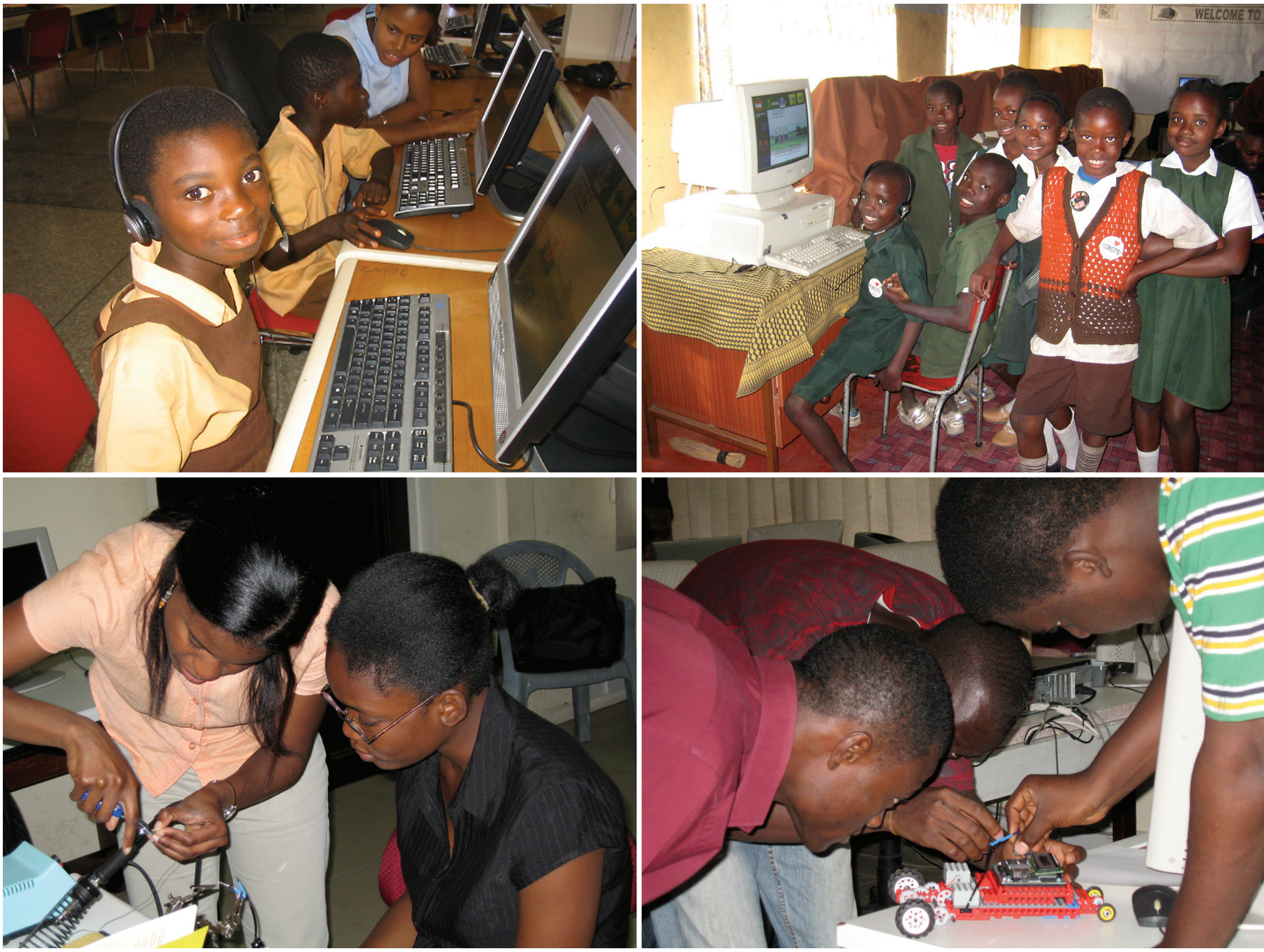
WHAT DO THE increasingly prominent news stories about $100 laptops, kids learning about computers through a "hole in the wall," and the power of mobile phones to educate, entertain, and connect people in remote regions have in common? It is the field of information and communication technology for development (ICTD), based on the belief that technology can have a large and positive effect on billions of individuals by helping them overcome the challenges so prevalent in developing regions. ICTD is not new—numerous important though relatively low-profile projects have been building the foundations of ICTD for many years. What's new are its name and, more important, the increased recognition the field has lately been receiving and its potential for exerting greater influence.

In this article we explore ICTD and examine the role that computer scientists can play in it. Our objective is to convince readers that although achieving all the goals of ICTD will not be easy, even their partial realization could have tremendous impact.

The motivation for this field comes from a new awakening to the vast gap in quality of life between the richest billion people on earth (who enjoy a variety of luxuries, including Internet access) and the poorest billion (who just barely eke out a living—and sometimes not). The base of the world's economic pyramid has an estimated population of four billion—over half of our planet's people—living on less than $2 a day.

In response to this awakening, scholars and practitioners have begun to explore the transforming power of information and communication technology when applied to the problems traditionally addressed in development. Can mobile phones provide income generation and facilitate remote medical diagnosis? How can user interfaces be designed so they are accessible to the semiliterate and even the illiterate? What role can computers play in sustainable education for the rural poor? What new devices can we build to encourage literacy among visually impaired children living in poverty? What will a computer that is relevant and accessible to people in developing regions look like? These are just a few of the questions being addressed in ICTD.

In other words, ICTD can be seen as harnessing the power of information and communication technologies, or ICTs, to take up many of the challenges of development. ICTs include technologies ranging from robotic tools and state-of-the-art computers to desktop



Educational initiatives by the TechBridgeWorld group at CMU explore the efficacy of technology tools like an automated English reading tutor. A more recent partnership with researchers from Ashesi University College in Ghana resulted in the country's first undergraduate robotics course.

PHOTOGRAPHS COURTESY OF TECHBRIDGEWORLD AT CARNEGIE MELLON UNIVERSITY

and laptop computers in their traditional forms; and from mobile phones, PDAs, and wireless networks to long-established technologies such as radio and television. The software components also span a wide range, from artificial intelligence and new algorithms, interfaces, and applications to the most prosaic programmed commodities.

Although the goals of international-development efforts vary, depending on the nature of each endeavor, the overarching goal of all such projects is the alleviation of the suffering caused by poverty and improvement of quality of life for the world's poor. The United Nations' eight Millennium Development Goals (MDGs) infused new energy into the world's development efforts and helped to focus them on concrete objectives—eradicating extreme poverty and hunger, improving maternal health, prevailing in the battle against HIV/AIDS and malaria, reducing child mortality, and achieving universal primary education, environmental sustainability, and a global partnership for development—to be met by the year 2015. Other development goals, not emphasized in the MDGs, include access to adequate shelter, information, avenues for income generation, and financial credit. The ongoing rural-to-urban shift of so much of the world's population has introduced a new set of problems as well, including increased vulnerability to disasters and the corresponding challenges for effective disaster responses. These are among the many international-development challenges that ICTD researchers and practitioners hope to address. They expect to reinvent the form, function, and applications of ICTs in new and creative ways so that such challenges may best be met.

From a CS point of view, ICTD can be seen as the next wave in ubiquitous computing. Historically, computers started as huge machines that filled rooms and were only relevant and accessible to a specialized minority. The next big wave was the home PC, which is now relevant and accessible to over one billion people worldwide. ICTD is perhaps the next revolution in computing—transforming the computer and the applications of computing so that this technology can finally become relevant and accessible to the other five billion people of the world.

Given its position at the intersection of technology and development, ICTD brings together a wide variety of actors in many different roles. Among the newest are computer scientists, and their role is potentially a big one, both for their beneficiaries and themselves. It can change the image of the computer science discipline, the nature of the PC, and the future of the field.

A crucial requirement for success

in ICTD, however, is interdisciplinary collaboration—working with scholars and practitioners from many different fields. Sociologists, ethnographers, and anthropologists, for example, can provide valuable information about the communities intended to benefit from ICTD. This information, regarding such things as cultural practices, traditions, languages, beliefs, and livelihoods, must guide the design and implementation processes for successful solutions in ICTD.

Economists and political scientists play important roles in ICTD as well by designing new economic models, marketing strategies, and governmental policies that affect the economic viability and sustainability of technological interventions. Social scientists also play a crucial role in evaluating the impacts and outcomes of ICTD projects using both qualitative and quantitative methods. They observe and predict how people in developing regions interact with technology, and they aim to affect social systems for adopting technology-aided solutions without disruption to the community. Thus computer scientists working in the field of ICTD must quickly learn to work with this variety of scholarly players, to benefit from their points of view, and to complement them wherever possible.

ICTD does not only cross disciplines; it also transcends the boundaries of academia and involves multiple sectors. This reality obliges ICTD researchers to work with practitioners, government representatives, multilateral institutions such as the United Nations, nonprofits, nongovernmental organizations, and even the private sector, whose interest in ICTD begins as it seeks access to emerging markets and new avenues for corporate social responsibility. Many of these sectors' people have been addressing the challenges of development for decades, and their efforts should profit from the addition of professionals in CS and related fields who will contribute new perspectives and their useful styles of rigor, critique, and innovation.

ICTD is therefore a truly global undertaking with a grand vision. It brings together numerous players, across geographic, socioeconomic, regional, disciplinary, and sectoral boundaries, who must work together if we are to improve the quality of life for the least privileged on our planet.

Although the cause is noble and the impact can be large, ICTD must ultimately be judged on its research value—and in particular, its research value in computer science.

The Many Challenges of ICTD

Given its enormous ambitions and multidisciplinary requirements, ICTD presents its researchers with a variety of challenges. They include adapting to unfamiliar cultures and traditions, ensuring accessibility to local languages and multiple levels of literacy, overcoming the barriers of misinformation and mistrust of technology, creating solutions that work within the local infrastructure, and many more. For example, networking must work in circumstances with low bandwidth, intermittent bandwidth, or no bandwidth at all. Computers must operate reliably in environments characterized by dust, heat, humidity, and inexperienced users. User interfaces must accommodate semiliterate and illiterate users. And software applications must be sufficiently intelligent to provide useful, accessible, and relevant services to populations that might be interacting with a computing system for the very first time.

Further, ICTD field tests often require considerable ingenuity, whether they involve accessing target communities, setting up long-term studies, transporting equipment, observing the logistics and legalities of export control laws, addressing safety concerns, and establishing trust and common ground with partnering organizations that cross cultural and geographic boundaries. And to begin with, researchers must be entrepreneurial in obtaining funding for their research, as ICTD is not yet an established field with reliable funding sources.

Although the cause is noble and the impact can be large, ICTD must ultimately be judged on its research value—and in particular, its research value in CS. Like other multidisciplinary fields, ICTD must be simultaneously present in multiple communities, each of which may have it own value system for research. Even within computer science, ICTD is judged differently by different CS communities.

In the human-computer interaction (HCI) community—for example, at the annual ACM CHI conferences—ICTD has been well received, as HCI is multidisciplinary by nature and already deals both with quantitative and qualitative research. Moreover, developing-region users differ in their employment and adoption of technology and thus comprise an important research direction for HCI professionals. In fact, HCI is arguably the easiest discipline within CS in which to work on ICTD research. Other areas with some inherent compatibility include systems, networking, databases, and AI. For example, in systems and networking, which are not as multidisciplinary as HCI and more quantitative in character, ICTD work is less natural, but it can still fit well when technology innovation and novel usage are involved. Examples from top-tier conferences include work on delay-tolerant networking, distributed storage, and novel MAC-layer protocols for long-distance WiFi. In these kinds of approaches to ICTD research, there must be a core technical nugget in addition to real-world deployments.

However, research requires a great deal of effort per published report, given the challenges of deployments; over the long term, ICTD researchers must aim to produce papers that are fewer in number but of higher impact. Moreover, it must be noted that ICTD tends to be driven by the solving of a problem rather than by technological innovation (often, in search of a problem), which means that many ICTD projects may not have a core technical nugget after all. Such problems, although highly satisfying to solve, are harder to claim as CS research.

For most projects, the real research is in actually discovering the specification of the problem via repeated fieldwork and deployments, which is similar in feel to iterative design in HCI. Although HCI is an exception, CS does not generally value problem discovery, especially if the end solution is simple (had we known to apply it). Researcher Matthew Kam went through such iteration to create effective educational games on cellphones:[3]

- Evaluating 35 existing games for PCs with village students.
- Creating 10 test games for English as a second language (ESL) and testing them with 47 students.
- Studying 28 traditional village games to make the games more intuitive (compared to Western games).
- Implementing a new set of games.
- Leading an ongoing multiyear study on the educational value of these games.

Overall, this process has taken over four years and continues to this day.

ICTD is also developing its own community values over time. The clearest values so far are novelty and on-the-ground empirical results, both quantitative and qualitative. Less clear are the values surrounding repeatability, rigor, and *generalizability*, and least clear is how to merge the values of qualitative fields such as anthropology or ethnography with those of CS. Consider generalizability: CS values generalizable results as an indicator of potential impact, while qualitative researchers often emphasize the differences in groups or users and aim to broaden the dialogue. This leads to placing value on reusable technology frameworks, such as HCI toolkits, that can be customized and easily localized. We discuss one such framework here for mixed paper/phone applications. ICTD is also creating its own scholarly forums for discussing and disseminating this work. The International Conference on Information and Communication Technologies and Development and the International Conference on Social Implications of Computers in Developing Countries are two examples.

What about Sustainability?

Long-term impact requires that ICTD projects be self-sustaining. First, after the researchers leave and the money stops flowing, does the project continue? Second, can it be replicated in other contexts?

Sustainability is challenging to define, and researchers disagree on the details. Most agree on *financial* sustainability as a key element: the deployment must produce enough income to at least cover its costs. In this view, philanthropy is acceptable for "kick starting" a project, but not for supporting routine operational costs. Similarly, while projects typically need not be wildly profitable, they should at least be cash-flow positive, as credit can be challenging.

The operating-cost issues add significant constraints to ICTD solutions. They include not just the cost of the technology but also availability (uptime), power requirements, potential for theft, and logistics. One common approach to financial sustainability is to commercialize a solution; this has worked well for mobile phones and treadle pumps, for example. Even if a for-profit venture is not the purpose, researchers must essentially address the same issues of costs, cash flow, awareness (marketing), and ongoing support.

Operational sustainability is the capacity of the permanent staff to keep the project going technically (without the researchers). In theory, financial sustainability enables operational sustainability (by paying for it), but in practice it cannot do so all by itself. This is because of limits on local skills, supplies, and logistics. Solutions must be not only easy to use, but also amenable to straightforward diagnosis and repair with limited training.

Training costs are actually underrated. ICTD projects, particularly in rural areas, cannot view training as a one-time activity needed only when the project starts. Once trained, IT workers are often tempted to leave for better jobs in urban areas or other countries. Thus training is a recurring cost, and it must be short and effective.

These kinds of sustainability are fundamental to scaling a successful pilot project. Unfortunately, development-work pilots rarely turn into large-scale self-sustaining successes. Typically the pilot is small enough and has enough researchers involved (with their own support) that the financial and operational issues do not really hinder it. Thus the pilot is mostly useful to validate prototypes and assess community reactions. The understanding of financial sustainability requires a longer trial with detailed accounting and no hidden subsidies (unless they are expected to continue at scale); it also requires dealing with replacement costs and expected equipment lifetimes. Operational sustainability must be evaluated via detailed tracking of problems and how and by whom they were solved. In both cases, the system evolves to reduce costs or simplify operation.

Finally, *replication* is the process of moving a successful project to a new environment. As developing regions are quite heterogeneous in many respects, projects typically need some adjustments to work well with new partners, a different culture, or a different government. Both scaling and replication are active areas of multidisciplinary research, and CS has a critical role to play, given its direct impact on sustainability.

A Few Sample Projects

We have selected four sample ICTD projects that illustrate some of the issues discussed thus far. The projects focus on four different topics—telemedicine, assistive technology, microfinance, and education—all in the context of developing regions. Each example highlights different challenges and characteristics of the ICTD field. Together, these projects reflect CS-related innovation in the areas of systems, networking, HCI, and AI. The past proceedings of the International Conference on Information and Communication Technologies and Development offer a much larger sampling of current or recent research efforts in the ICTD field. Several other examples and an overview of ICTD are also provided in a recently published special edition of *IEEE Computer.*[8]

Rural Telemedicine: The Aravind Eye Care Hospital in southern India is a world leader in high-volume low-cost eye care. Working in the state of Tamil Nadu, Aravind served over 2.4 million patients last year and performed over 280,000 cataract surgeries. More than half the patients receive free or discounted eye care—they are subsidized by paying customers—and the hospitals have been financially self-sustaining for decades.

Despite this success, until recently Aravind had limited reach into rural areas; patient surveys indicated that most patients came from within 20km of a hospital and that only 7% of rural patients had access to any kind of eye care. After several iterations, it became clear that the solution was to create rural vision centers (VCs) consisting of 1–2 rooms, a nurse, a technician (to make eyeglasses), and notably the means for high-quality doctor/patient videoconferencing. This "video solution,"[7] developed at UC Berkeley, uses novel long-distance WiFi links that are low-cost, low-power, and typically deliver 4Mb/s–6Mb/s between the hospital and the VC over distances ranging from a few to tens of kilometers. (The same basic technology has also been extended to go 382km in Venezuela.)

Having successfully completed a five-VC pilot in early 2006, Aravind now has 24 VCs in operation via a mix of WiFi and DSL (in more urban areas). Some 5,000 patients use the video service per month, with over 100,000 through the end of 2008 having used the WiFi links. Of these 100,000, over 15,000 were effectively blind (primarily due to refractive problems or cataracts), but can now

Researchers from CMU's TechBridgeWorld are working with the Mathru School for the Blind outside Bangalore, India, to enhance the teaching and learning process for writing Braille through the use of a low-cost writing tutor that gives audio feedback to students.

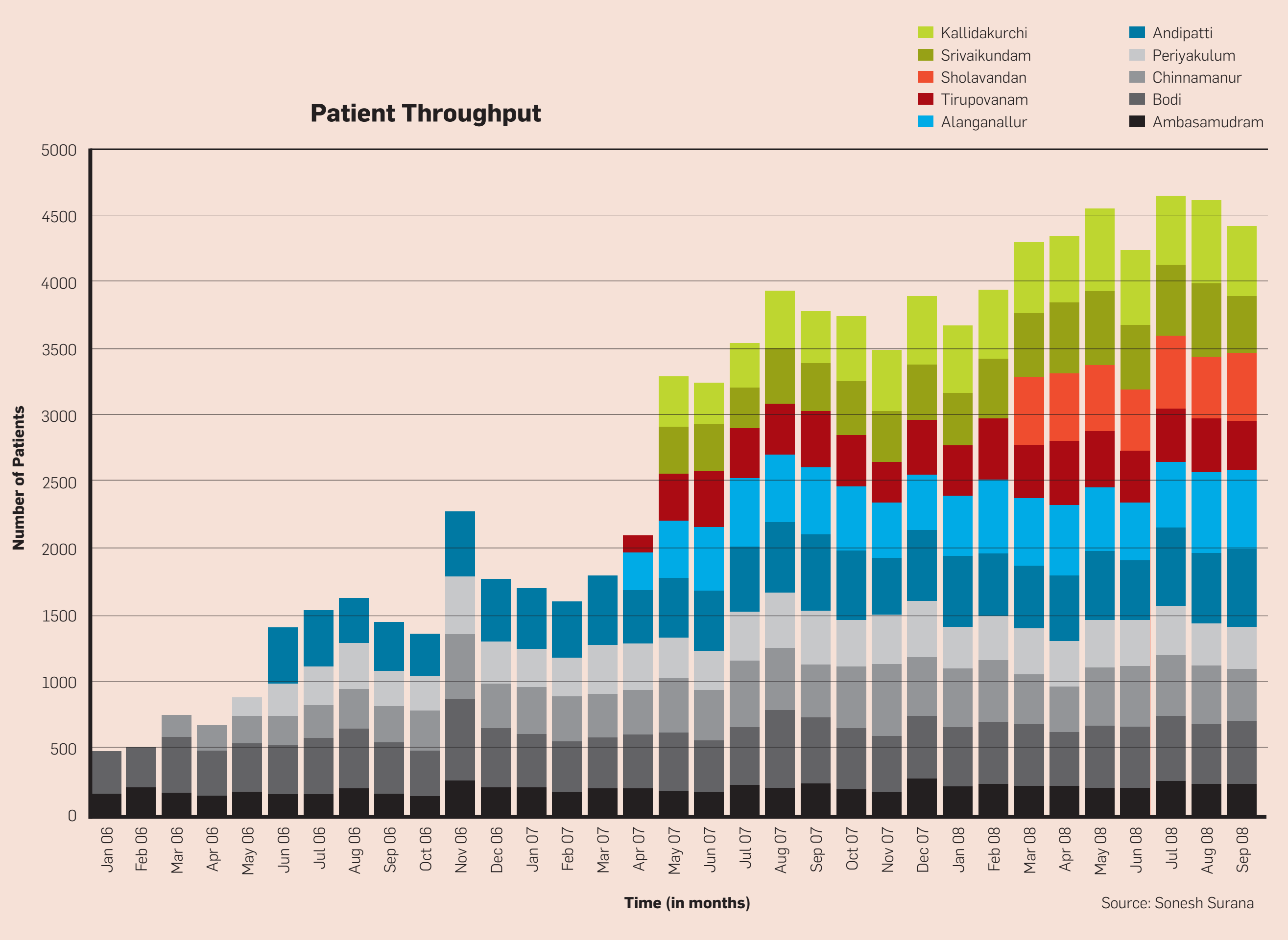
PHOTOGRAPHS COURTESY OF TECHBRIDGEWORLD AT CARNEGIE MELLON UNIVERSITY see well; 85% of them have been able to return to income generation. This example shows how the combination of basic needs and large volumes in developing regions enables ICTD research to have great impact. Aravind recently won the $1M 2008 Gates Foundation Award for Global Health, in large part because of the reach of these vision centers.

Assistive Technology: The Mathru School for the Blind is a residential facility that provides free education, clothing, food, and health services to visually impaired children from socially and economically deprived families from remote parts of India. The school is located in the residential area of Yelahanka, a suburb of Bangalore. Teaching Braille, the only means of literacy for the blind, is an important part of the curriculum at Mathru. However, learning to write Braille using the traditional and slate and stylus is not an easy process, for several reasons. First, Braille must be written from right to left in mirror-image format so that the correct Braille characters can be read when the paper is removed from the slate and flipped over. Second, students get delayed feedback; they must wait until their writing is complete and the paper has been removed and read. Third, when the teachers themselves are blind, it is difficult to diagnose problems in the students' writing process by simply reading the end product. Finally, motivation for learning to write Braille is very low because the process is tedious and sometimes even physically taxing for young students.

Researchers from the TechBridgeWorld group at Carnegie Mellon University are working with Mathru to enhance the teaching and learning process for writing Braille using a slate and stylus. This effort has resulted in a low-cost Braille writing tutor that gives audio feedback to the student as he or she forms characters with the stylus. This Braille tutor,[2] first designed, implemented, and field-tested in 2006, has been enhanced through an iterative design process to provide several features. They include teaching basic Braille in several languages, teaching basic math symbols, adapting the operational mode to cater to specific student needs, and several educational games that motivate students to learn the skill of writing Braille. This ongoing research has expanded to several new partnerships, including groups in Qatar, Zambia, and China.

Microfinance Support: The Nobel Peace Prize for Mohamed Yunus brought overdue attention to the powerful role of microfinance in developing regions. Such services are in dire need of technological support, not only for basic accounting but also to reduce fraud and satisfy government mandates for reporting. The required reports in India, for example, specify multiple copies of the same tables

The growth in centers (one per color) and patients in the Aravind telemedicine project in India.



in different formats, which are easily done with a spreadsheet but tedious and error-prone on paper, which has been the typical mode.

Tapan Parikh, in his dissertation work at University of Washington, developed a system called CAM[6] (short for 'camera') that combines the comfort and tangible nature of paper with the power of mobile phones. Two-dimensional barcodes on the paper guide data entry on the phone and help to manage document flow. In addition to workflow support, CAM uses the keypad for numeric input and provides voice feedback, both of which have been well received by semiliterate rural users. This system is now under trial with 400 microfinance groups in India.

Educational Technology and Technology Education: Project Kané,[1] an initiative of the TechBridgeWorld group at Carnegie Mellon University, explores the efficacy of technological tools in improving English literacy for children in developing regions, with a focus on Africa. The project started with a three-week pilot study in Ghana that tested the feasibility and impact of using an automated English-reading tutor to improve the level of English literacy among children from low-income families in Accra. This study gave preliminary indications that the tutor had a positive impact on the students' performance on spelling and fluency tests. It also identified several important factors for success, such as the need to include some local stories familiar to the children and the necessity to narrate the tutorial (on how to use the automated tutor) in a voice with a Ghanaian accent. Based on this initial success, the pilot was scaled to a six-month study that included three groups of children from very different socioeconomic backgrounds, and it has also been replicated in Mongu, Zambia.

The automated tutor used in these studies was not designed for developing regions, however, and it was clear that new educational-technology tools with that focus were needed. This goal is being pursued through a new partnership between TechBridgeWorld researchers and alumni of the course in robotics and artificial intelligence—Ghana's first—taught at Ashesi University College.

Ayorkor Mills-Tettey, a doctoral candidate in robotics at Carnegie Mellon University and a native of Ghana, had spearheaded a collaborative project between TechBridgeWorld and Ashesi University College to design and teach that course[5] at Ashesi, a private, accredited, nonsectarian college dedicated to training a new generation of ethical and entrepreneurial leaders in Africa. The collaboration between the two universities led to a summer course designed and taught with careful consideration of the local context, infrastructure, and resources.

Several students who took this course have now graduated and have followed different employment paths; some headed to industry (including a startup company for developing mobile applications) and others to graduate school. Empowered with a strong technology education, some of these students are now collaborating with TechBridgeWorld researchers to design, implement, and field-test educational technology tools to improve literacy in their homeland.

Looking to the Future

We believe that technology, along with good governance and macroeconomics, represents the path forward for the majority of the world's people. Consider that in 1970, South Korean and African incomes were similar; but the rapid relative rise of South Korea shows what is possible, due in large part to technology.[4] We believe that proactive research and development of ICTs appropriate for developing regions can lead to similar growth and prosperity over time and to an improved quality of life in the immediate future.

Today we have lots of examples and anecdotes about high impact from ICTD in developing regions, but the field remains ad hoc and largely without the benefit of the innovative thinking that more computer scientists would bring to bear. The situation could change substantially, however. The core costs of computing and communication have dropped to a point that enables CS to affect everyone, especially when combined with the flexibility inherent in software that enables low-cost customization for a wide variety of contexts. This combination makes CS uniquely positioned among all disciplines to have immediate and large-scale impact. But the role of CS in development is essentially a community decision, involving whether we value this work or not. For example, will ICTD be a viable path to a tenure-track CS faculty position?

We can say that although the challenges are great, ICTD is both intellectually rewarding and very attractive to students at all levels. With several recent reports citing the dwindling numbers of students interested in studying CS, perhaps ICTD is one answer. It may help motivate a new generation of computer scientists to contribute their knowledge, talents, and energies toward solving some of the world's most pressing problems. **C**

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