Some Computer Science Issues in Creating a Sustainable World

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Computer scientists have a role to play in combating global climate change.

Among the biggest challenges the world faces today are the climate crisis and the broader issues of environmental sustainability raised in books such as Jared Diamond's *Collapse: How Societies Choose to Fail or Succeed* (Viking, 2004). Part of the solution to this problem depends on climate science, breakthrough technologies, and policy changes.

However, as Daniel Quinn argued in his 2002 address, "The New Renaissance" (http://ishmael.org/Education/Writings/The_New_Renaissance.shtml), "What we must have (and nothing less) is a whole world full of people with changed minds. Scientists with changed minds, industrialists with changed minds, school teachers with changed minds, politicians with changed minds." He goes on to describe how each of us must find a more sustainable way to do things in businesses and at home.

A commonly stated goal is to reduce world energy use to 1990 levels, thereby stabilizing atmospheric CO_2 emissions at 350 parts per million (J. Hansen et al., "Target Atmospheric CO2: Where Should Humanity Aim?" 18 June 2008, http://arxiv.org/abs/0804.1126v2, http://350.org).

Computer scientists can help reach this goal in four ways. Two of these involve mitigating the direct negative impact of computers—their power consumption as well as the economic and social costs associated with the manufacturing, maintenance, and disposal of components. The other two relate to the indirect positive impact of computers—their ability to increase energy efficiency by changing systems and ways of being; to potentially reduce world emissions by as much as 15 percent by 2020, according to the Climate Group's June 2008 report (www.smart2020.org); and to help provide answers to important scientific questions.

COMPUTATIONAL ENERGY CONSUMPTION

A Forrester Research report projects the number of personal computers in use in the most populous countries to double to 2.25 billion by 2015 (S. Yates, "Ranking PC Growth Markets," 10 July 2007). Embedded devices are becoming pervasive; by 2011, there will be three per person on the planet (www.microarch.org/micro35/keynote/Agerwala.pdf).

According to the Climate Group, total energy consumption by computers—including the power consumption and embodied energy of data centers, PCs and peripherals, and networks and devices—accounted for 830 million metric tons of carbon dioxide, or 2 percent of the total world carbon footprint, in 2007. As Figure 1 shows, these figures are roughly equivalent to the total CO_2 emissions of Nigeria, Iran, and Poland, respectively. Data centers alone use almost 0.5 percent of the world's energy, and this figure is likely to quadruple by 2020.

Lowering the energy cost of computation will depend on our ability to reduce processor cycles, communication needs, and architectural inefficiencies. For example, according to the US Environmental Protection Agency, power adaptors consume 11 percent of US electricity, yet available design changes soon to be mandated by the Energy Star program (www.energystar.gov) can reduce their energy use by 30 percent.

Hardware

Hardware advances provide new opportunities for compile-time or dynamic efficiency improvement. For example, heterogeneous chip multiprocessors can achieve four to six times energy savings per instruction (R. Kumar et al. "Heterogeneous Chip Multiprocessors," *Computer,* Nov. 2005, pp. 32-38).

Recent research by Samuel Williams and colleagues explores supercomputing programming paradigms for a modified Cell processor that can achieve up to 100 times the energy efficiency of leading competitors ("The Potential of the Cell Processor for Scientific Computing," *Proc. 3rd Conf. Computing Frontiers,* ACM Press, 2006, pp. 9-20).

Networks

Smarter networking can likewise reduce communication costs. For example, intelligent routing protocols can ensure the use of minimum energy routes, and media access control (MAC) protocols can reduce energy consumption in idle times during data transmission and reception (C. Sengul and R. Kravets, "Heuristic Approaches to Energy-Efficient Network Design Problem," *Proc. 27th Int'l Conf. Distributed Computing Systems,* IEEE CS Press, 2007, p. 44).

Although much of the original work in energy-aware communication comes from the wireless domain, researchers have leveraged these techniques in the wired domain. Protocols such as Adaptive Link Rate use machine learning to lower desktop computers' energy consumption by reducing Ethernet transmission rates when utilization is low (P. Patel-Predd, "Energy-Efficient Ethernet," *IEEE Spectrum,* May 2008, p. 13).

Data centers

Server-based systems that support many different remote individuals require a different set of power-management strategies. For example, Ripal Nathuji and Karstan Schwan tackle the problem through virtualization ("VirtualPower: Coordinated Power Management in Virtualized Enterprise Systems," *Proc. 21st ACM SIGOPS Symp. Operating Systems Principles,* ACM Press, 2007, pp. 265-278).

Although managing energy in a data center might seem to be only a matter of scale, researchers at HP Labs have shown that it is also necessary to consider the machines' thermal properties (R. Raghavendra et al., "No 'Power' Struggles: Coordinated Multi-Level Power Management for the Data Center," *ACM SIGARCH Computer Architecture News,* Mar. 2008, pp. 48-49).

Luiz André Barroso and Urs Hölzle argue that machines should consume energy in proportion to the amount of work performed ("The Case for Energy-Proportional Computing," *Computer,* Dec. 2007, pp. 33-37). However, achieving this goal in large data centers could significantly affect performance.

A recent Microsoft Request for Proposal highlights additional research needed to create power-aware systems (http://research.microsoft.com/ur/us/fundingopps/rfps/PowerAware_RFP.aspx). This includes benchmarks and metrics, integration and cooperation across system layers, advances in scientific computing and visualization, and innovations in everything from the physical layout of data centers to the structure of the average computer—for example, substituting flash memory for other types of memory.

ELECTRONIC WASTE

Almost as daunting as computing devices' growing energy consumption are the high costs associated with their production, support, upgrading, and retirement. Beyond the numerous resources used in the product life cycle—including water, fuel, and electricity—is the difficult-to-measure but often devastating impact computer-related waste has on human populations and the environment.

A recent Basel Action Network report ("The Digital Dump: Exporting Re-use and Abuse to Africa," 24 Oct. 2005, www.ban.org/BANreports/10-24-05/documents/TheDigitalDump.pdf) predicts that the US alone will retire approximately 3 billion units of electronics—primarily computers, monitors, and TVs—by 2010. Companies dump much of this refuse in developing countries, exposing millions of people to dangerous toxins such as

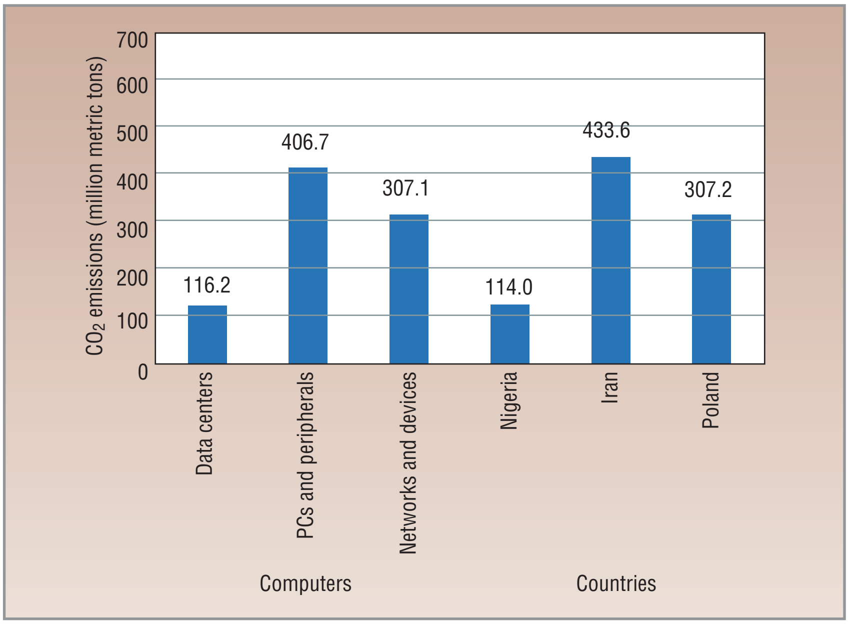

Figure 1. Carbon dioxide emissions from the energy consumed by data centers, PCs and peripherals, and networks and devices are roughly equivalent to those of Nigeria, Iran, and Poland and account for 2 percent of the total world carbon footprint.

Figure 2. To help reduce summer electricity usage in Chicago, the Center for Neighborhood Technology created an ambient orb that displays households' real-time energy cost. Photo courtesy of CNT/CNT Energy.

lead and mercury as well as wasting energy embodied in the devices.

Computer scientists can influence many steps in the computing life cycle (E. Blevis, "Sustainable Interaction Design: Invention & Disposal, Renewal & Reuse," *Proc. SIGCHI Conf. Human Factors in Computing Systems,* ACM Press, 2007, pp. 503-512). For example, one step toward eliminating electronic waste is reducing the need for new computers.

Innovative desktop grid computing projects such as the Berkeley Open Infrastructure for Network Computing (http://boinc.berkeley.edu), which grew out of SETI@home's efforts to search for extraterrestrial intelligence, can help with this. Virtualization, which allows many users to share one computer, also can help.

Incorporating modular chips or components makes it possible to replace a single part instead of an entire system. More radically, as networks become ubiquitous, we can create personal devices that are simple clients, shifting the more intensive computation to upgradeable servers and thereby reducing the need to replace every individual device.

However, this approach raises tradeoffs between personal privacy and control over data that researchers need to address. It also creates new challenges for designers: Can one device fit all needs? If not, what is the best way to distribute data over multiple devices?

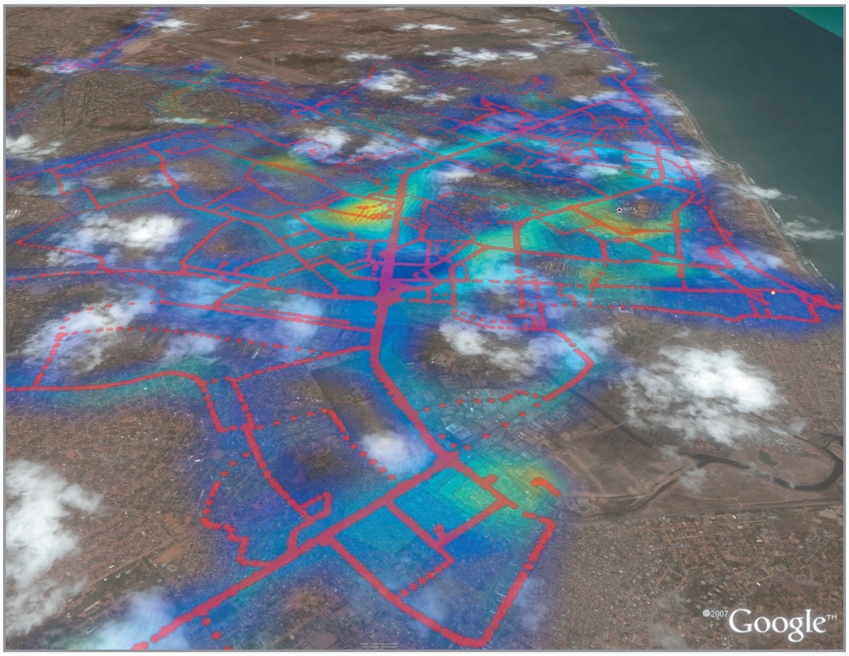

Figure 3. Emerging sensor-rich mobile computing devices make it possible for "citizen scientists" to capture fine-grained data on a large scale. This graphic of CO_2 emissions for a city in Ghana was obtained through taxi cab data. Image courtesy of Eric Paulos.

GLOBAL ENERGY CONSUMPTION

The Climate Group's recent report argues that computing technology could facilitate significant reductions in worldwide energy use, equalling as much as five times the projected growth in computational power consumption. Energy savings could be accomplished through recent or future innovation in motor systems, transport and storage logistics, power grids, and building design, management, and automation.

Computers' interactive nature provides an additional opportunity for energy reduction—by educating people, creating new ways of being, and changing behavior. For example, Columbia University's Educational Global Climate Modeling software (http://edgcm.columbia.edu) enables high school and college students to visualize climate change at home and in the classroom. This is possible because today's personal computers can run older climate models.

In 2006, Chicago's Center for Neighborhood Technology (www.cnt.org) helped reduce summer electricity usage by 3 to 4 percent by providing local households an ambient orb, shown in Figure 2, that displays the real-time cost of energy.

Cutting home energy use is one of the major ways in which individuals can shrink their carbon footprint. Even small changes can collectively have a large impact such as avoiding the need for a new power plant.

Wildly popular social-networking websites such as Facebook provide yet another lever to modify the energy-consumption habits of potentially millions of people (J. Mankoff et al., "Leveraging Social Networks to Motivate Individuals to Reduce Their Ecological Footprints," *Proc. 40th Ann. Hawaii Int'l Conf. System Sciences,* IEEE CS Press, 2007, p. 87). StepGreen.org is one Web 2.0 application exploring these ideas.

CLIMATE SCIENCE

The advent of the National Science Foundation's Cyber-Enabled

Discovery and Innovation initiative (www.nsf.gov/news/news_summ.jsp?cntn_id=108366) highlights the increased interest among researchers in applying innovations in computational thinking to all types of science, including climate science.

For example, recent advances in scientific computation are making it possible to better understand the impact of forest dynamics on carbon sequestration (D. Purves and S. Pacala, "Predictive Models of Forest Dynamics," *Science,* 13 June 2008, pp. 1452-1453).

The Earth System Grid (www.earthsystemgrid.org), a new project sponsored by the US Department of Energy's Scientific Discovery through Advanced Computing program (www.scidac.gov), is an example of a grid computing solution for managing access to and storing petabytes of data generated by such climate models.

Little data is available at the micro level about energy consumption, air and water quality, and other environmental issues. However, as Figure 3 shows, emerging sensor-rich mobile computing devices make it possible for "citizen scientists" to capture fine-grained data on a large scale (E. Paulos, R.J. Honicky, and E. Goodman, "Sensing Atmosphere," workshop position paper, *5th ACM Conf. Embedded Networked Sensor Systems,* 2007, www.cs.berkeley.edu/~honicky/sensys07.pdf).

This data could be integrated with information from location-tracking, geopositioning, and other sensing sources to, for example, determine air pollution levels for every block of every city, each consumer good's complete transportation costs, and accurate measurements of individual and societal carbon footprints.

Global climate change is one of the most pressing problems of our time. Government agencies, universities, and businesses are starting to step up and invest in research, but even more change is needed, ranging from standards and policies to research innovations and new businesses. Now is the time for computer scientists to use their skills and resources to help create an energy-efficient future.

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