1-1-2006

Integration of Low-Power Digital Circuitry into Undergraduate Curricula

Glenn Ellis
Smith College, gellis@smith.edu

Sarah Wodin-Schwartz
Smith College

Baaba Andam
Smith College

Israel Koren
University of Massachusetts Amherst

C. Mani Krishna
University of Massachusetts Amherst

See next page for additional authors

Authors
Glenn Ellis, Sarah Wodin-Schwartz, Baaba Andam, Israel Koren, C. Mani Krishna, and C. Andras Moritz

2006-874: INTEGRATION OF LOW-POWER DIGITAL CIRCUITRY INTO UNDERGRADUATE CURRICULA

Glenn Ellis, Smith College

Sarah Wodin-Schwartz, Smith College

Baaba Andam, Smith College

Israel Koren, University of Massachusetts-Amherst

C. Mani Krishna, University of Massachusetts-Amherst

C. Andras Moritz, University of Massachusetts-Amherst

Integration of Low-Power Digital Circuitry into Undergraduate Curricula

I. Introduction

Power-aware computing has become in recent years a significant area of research and development in both academia and industry[1,2]. Various techniques for reducing the temporal power and the long term energy consumption of embedded processors in general and mobile devices (e.g., cellular phones, PDAs and laptop computers) in particular, have been developed. Several new products whose main feature is lower power consumption have been introduced successfully into the marketplace. The techniques developed for achieving the reduced power and energy cover many phases of the computer system design including circuits, voltage scaling, micro-architectures and system software (i.e., operating systems and compilers).

Over the last ten years or so, power-aware computing has been transformed from a somewhat arcane and limited discipline to one of the most active areas in computer science and engineering. This trend has been fueled by the following:

- Processors are becoming ever more power-hungry, and their power densities (watts/ cm^2) are increasing rapidly. The power density of many modern processors exceeds that of a hotplate and that of the core of a nuclear reactor[3]. The problem of dissipating heat from a microprocessor is therefore becoming more acute. As feature sizes shrink, the fraction of energy lost to leakage will become significant. Leakage rises very rapidly with temperature: so running a processor hot will further increase power consumption, thereby setting up a positive feedback loop. Further, the processor failure rate increases with an increase in the operating temperature.
- Battery-powered applications have proliferated. Battery technology has not advanced as rapidly as processor power consumption, and this limits the mean time between recharges.
- The more obvious approaches to constraining power consumption, such as disk spindown and turning off the screen have already been implemented. More complex approaches are now being pursued for additional savings.
- The aggregate power consumption of computers is no longer a negligible fraction of the total power consumption in the United States[4]. Approaches to reduce such power consumption can therefore be expected to make a measurable impact on the overall power consumed in the country.

There has been very little done in electrical engineering curricula to develop students' skills and abilities to design efficient digital circuits. The Institute of Electrical and Electronics Engineers (IEEE) recommends that low-power digital circuit design be taught in the undergraduate curriculum for electrical and computer engineers[5]. Some institutions have begun to incorporate low power digital circuits into the electrical/ computer engineering curriculum, but their methods of implementation have added to the course load of the undergraduates and are all optional. King Fahd University of Petroleum and Minerals in Saudi Arabia has developed a senior level course, *EE 415 - Analog Integrated Circuits Analysis And Design,* in which a major part of the course discusses low-power in their circuit design[6]. The University of Utah has redone its entire electrical engineering program with a grant from the National Science Foundation to enhance the students' comprehension and retention of electrical engineering concepts. They now offer two electives where students can learn about low-power digital circuits through independent projects[7].

It is clear that these schools and others[8-10] agree that teaching power-aware techniques at their institutions will enhance their undergraduate curriculum. However, in order for students to learn the importance of low power digital circuitry, the material must be incorporated into the existing curriculum. While these schools are attempting to include low power digital circuits, they are not utilizing techniques that will optimize the students understanding and appreciation for the material. The classes offered at these other institutions are elective rather than required. The benefits to teaching these skills in a modular form are that the students will experience the material in many different forums and the modules can be incorporated into required courses. The repeated use of sustainable technologies in the class room will precipitate sustainable techniques in the field.

At the University of Massachusetts (UMass) and Smith College there is an impetus to attract women and minorities into the sciences and engineering. By teaching sustainable techniques these select student groups will be attracted to the programs. This trend is observed and documented in the book <u>Talking About Leaving</u>. "Both male students of color and all women tend, more often than white males, to enter S.M.E. [Science, Math, Engineering] majors with altruistic career motivations…[they] reject job opportunities they had already been offered in favor of work which incorporated preferred lifestyles, values and social goals."[11]. The study described in the paper "Deconstructing Engineering Education Programs to Foster Diversity" was conducted to determine the motivations behind the selection of majors for women and minorities. They conclude that most students chose majors with which they can personally identify. The sciences and engineering are designed for a white male audience. One example from their report is based on textbook content in the sciences and engineering. "Traditional course materials are known for their white male bias. In 1997 Jill Marshall and James Edward analyzed introductory physics classes and textbooks at Utah State University. … One physics text mentions 118 males and only 2 female physicists…In some textbooks, women and minorities appear in illustrations but are absent from the text."[12] This paper also shows that women and minorities shy away from the sciences because they have a much stronger connection to their societies. "The emphasis of the traditional engineering curriculum is on mathematical problem solving, drawing a boundary around a problem and not allowing sentiment or society or feeling or personality to intrude, causes students to choose between engineering and personhood. Some 'stick it out', but many choose to drop engineering in favor of personhood."[12] Any method that lends a sense of purpose to engineering applications attracts the under-represented groups to the field. Low power digital circuitry topics give students the opportunity to apply the abstract concepts of circuit design into a technology to benefit their society.

II. Modules

Studies show that students retain more knowledge if they apply it in more than one venue. "Studies of transfer from learning one text editor to another illustrate the importance of viewing transfer from a dynamic rather than a static perspective. Researchers have found much greater transfer to a second text editor on the *second* day of transfer than the first."[13, 14] By developing modules to teach low-power technologies in different undergraduate circuits classes at all levels, freshman to senior, students are not only more likely to understand the technical concepts, but they will learn the value of sustainability. This is a challenging value to teach because sustainable methods are often more costly than less environmentally sound techniques. Digital circuitry offers a perfect venue to showcase cost effective energy saving practices. These modules offer an opportunity to educate a more environmentally conscious engineer by promoting environmentally safe technologies.

UMass in collaboration with Smith College is developing a series of learning modules to be incorporated into all levels of the electrical and computer engineering curriculums. The modules will promote sustainability through the design of low power digital circuits using learner centered techniques to optimize student comprehension and knowledge retention. The modular structure will allow the concepts to be taught in a variety of classes. Because engineering students are typically required to complete at least 25 classes for their major, it would be challenging to incorporate another full course. Since this material is too important to maintain elective status as some schools have allowed, a modular design is ideal.

Overview

About 20 modules are being created that consider architectural, operating systems, compiler, and hardware issues in power-aware systems. Associated with each module, are (a) background information at the appropriate level, (b) list of references for further study, (c) description of the problem(s) to be studied, and (d) relevant software.

There are six topics over which these modules range: architecture, voltage scaling, operating systems and middleware, compilers, VLSI, and wireless networks. A brief description of some representative module is provided below.

Architecture

- **Static and Dynamic Power**: This module explains the two types of power consumption in Complementary Metal Oxide Semiconductor (CMOS) circuits. Techniques to mitigate the two are covered.

- **Using an Architecture-Level Power Simulator. Breakdown of Energy Consumption**: An important part of power-aware design is tracking down where the energy is being spent through the use of power simulators. The focus of this module is on architectural and circuit-level power simulators, like Wattch and HSpice.

- **Fetch Throttling**: The fetch unit in a processor may bring in instructions at a higher rate than they can be consumed by the execution unit resulting in a waste of energy. Techniques to throttle back the fetch are studied in this module, and laboratory exercises are included to measure their energy impact.

Voltage Scaling

When the voltage is scaled down the power consumption drops by a substantial amount but the execution time increases. The energy consumed in executing a given task, which is the product of power and execution time, decreases as the square of the voltage. The implications of this tradeoff in real-time systems are studied in the cases of independent tasks and task graphs.

Operating Systems and Middleware

- **Disk spindown algorithms**: Disks consume a substantial amount of energy so it makes sense to spin them down when they are not going to be used for some time[15]. The recent history of disk usage is used to predict the future usage. If this prediction is incorrect, it can actually consume more energy in spinning down and then up again frequently. In this module, mathematical tools to derive a good disk spindown policy are covered including Markov decision theory and Bayesian approaches.

Compilers

- **Power Impact of Conventional Program Transformation Techniques:** Compiler transformations can have a significant impact on overall power consumed. While conventional loop transformations such as loop-unrolling, have been shown to improve performance, they impact power consumption.

  For example, loop-unrolling requires multiple copies of the loop body, that increases the code size and thus could increase the instruction fetch and off-chip memory related energy consumption. It is often beneficial to reduce the code size to decrease the fetch related power consumption.

  The purpose of this module is to expose students to various compiler transformation techniques and study their power impact for various applications.

VLSI

- **Circuit Styles**: Various circuit styles have significantly different power-performance characteristics. This module covers techniques to evaluate static and dynamic circuit styles from point of view of power consumption. Circuits will be developed and simulated with Hspice and PowerMill. Example circuits include decoders, FSMs, SRAM cells and sense amplifiers. Tradeoffs between area, noise margins, delay, static and dynamic power consumption will be investigated.

Wireless Networks

Our modules concentrate on networks based on very simple nodes, for example, the motes designed at Berkeley[20]. Such nodes are characterized by a very limited power supplies (typically powered by small batteries). These sensor nodes will expire when their batteries run out. Managing the power consumption is therefore vital to extending the lifetime of such networks.

- **Sentry approach to reduction of power consumption**: In many applications, like sensing the environment, the event being looked for is rare, and thus, it is wasteful to keep all the nodes on all the time. Instead, a subset of the nodes act as sentries, and scan the environment, while the rest of them sleep[24]. When an "interesting" event occurs, the sentries awaken other nodes. To permit uniform usage of node batteries, nodes take it in turns to be one of the sentries. This module covers the tradeoffs inherent in this approach using the TOSSIM simulator[25] augmented with a power consumption evaluator.

III. Implementation and Assessment

Three courses at Smith College and UMass now include low-power techniques. Data have been collected from each of these classes, *Digital Circuits & Computer Systems* (CSC 270/EGR 251), and *The Computer Architecture* (ECE 568/668). The results from these courses will be presented as a gauge of student content understanding and attitudes.

The Hardware Organization and Design class (ECE 232) provides an introduction to computer architecture and hardware design with an emphasis on computer design techniques from a hardware perspective. The class is taken at the sophomore level: it consisted of 122 students (4 women).

The Computer Architecture class (ECE 568/668) offered at UMass is designed for juniors, seniors, and graduate students and includes advanced material about the structure of digital computers. Topics include: the organization of sub-systems such as the memory and I/O; the interplay between hardware and software in a computer system; the von Neumann architecture and its modern competitors. The class enrollment was 46 students (7 women, 19 undergraduates) for Fall 2004 and 32 students (5 women, 13 undergraduates) for Fall 2005.

Table 1 shows the change in student knowledge related to power consumption. While it was clear that there was already some understanding of the subject at the beginning of the class, all of the questions showed a higher level of understanding in the post-test. The most notable increase was in the estimation skills measured in question 5. The 28% increase (Fall 2004) and the 44% increase (Fall 2005) in the correct estimation of “farm” power consumption show that the students learned the concepts rather than memorized formulas.

Survey Questions	Percent Correct			
UMass Architecture Class data	Fall 2004		Fall 2005	
	Pre-Class	Post-Class	Pre-Class	Post-Class
Q1. A high-end processor (e.g., Alpha, Pentium, PowerPC) typically consumes a. 100 mW to 1 W b. More than 1 W but less than 10 W c. More than 10 W but less than 100 W d. More than 100 W	19%	38%	41%	67%
Q2. To save energy, laptops usually spin down the hard disk if it has not been used for some time. Suppose you have two workloads, A and B, each of which has the same total number of disk accesses. However, the accesses in A are tightly clustered: they all occur within a small window of time. The accesses in B are spread out evenly. Would disk spin down save: a. More energy for A than for B? b. More energy for B than for A? c. Roughly the same amount of energy for A and B?	56%	72%	63%	72%
Q3. A laptop running off its battery is: a. Power-constrained but not energy-constrained. b. Not power-constrained but energy-constrained. c. Neither power- nor energy-constrained. d. Both power- and energy-constrained.	22%	38%	41%	83%
Q4. By reducing the supply voltage (to some extent), we can reduce processor energy consumption. a. True b. False	81%	84%	66%	67%
Q5. A server "farm" in a major data center typically consumes: a. Less than 1 kW. b. 1 kW to 10 kW. c. More than 1 kW but less than 100 kW. d. More than 100 kW.	19%	47%	28%	72%
Q6. If the amount of instruction-level parallelism is high, would you expect: a. The fetch unit to be throttled less. b. The fetch unit to be throttled more. c. No impact on the fetch throttling.	11%	31%	31%	72%

Table 1—UMass ECE 568/668 Architecture Class Data for Fall 2004 and Fall 2005

In addition to knowledge and problem solving skills, the class also focused on increasing student awareness that the aggregated power consumption of computers is no longer a negligible fraction of the total power consumption in the United States and that being fully aware of the energy-saving techniques is one of the most active areas in computer science and engineering. Following are the results of the post-test regarding the students' attitude towards power-aware computing techniques in Fall 2004:

- 61% students strongly agreed or agreed that "I fully understand the impact of the power consumption of modern processors on the environment after the lectures."
- 79% students strongly agreed or agreed that "it is necessary to incorporate power-aware computing techniques into both undergraduate and graduate curricula."
- 57% students strongly agreed or agreed that "I am interested in the research area of energy-saving now."

For Fall 2005, the results were as follows:

- 44% students strongly agreed or agreed that "I fully understand the impact of the power consumption of modern processors on the environment after the lectures."
- 78% students strongly agreed or agreed that "it is necessary to incorporate power-aware computing techniques into both undergraduate and graduate curricula."
- 34% students strongly agreed or agreed that "I am interested in the research area of energy-saving now."

The Digital Circuits & Computer Systems class (CSC 270/EGR 251) at Smith College, composed of 6 female students, was a combination of a standard digital circuits class with a digital logic class (Boolean algebra, Karnaugh maps, etc.). One class period was devoted to power saving techniques. Slides from the Hardware Organization and Design class at UMass were modified and used to teach about the tradeoffs between faster computing with higher power consumption and slower computing with lower power consumption. Different types of central processing units were discussed to show how many techniques could be used to achieve similar ends via different means. The students ranged from sophomore to senior level.

Students were surveyed at the beginning and end of the class. The results are shown in Table 2 and Figure 1. Table 2 indicates that by the end of the class there was a clearer understanding of how power in a system is used and measured. Figure 1 shows an increased interest in learning about power saving techniques. This marks a major success of the lesson; the students are embracing efficient technologies and are excited to incorporate that knowledge into their future designs. There were no other noticeable changes in the students' opinions of the material because they were overwhelmingly positive at the start of the class. This is not surprising given the strong focus on sustainability in the Smith program.

Survey Questions	Percent correct solution	
Smith College Digital Circuits Class	Pre-Class	Post-Class
Q1. What metric would be useful for finding a balance between power used by a circuit and its speed?	33.3%	100%
Q2. When comparing a ripple carry adder (RCA) to a carry look ahead adder (CLA), which one of the following statements is true?	33.3%	83.3%
Q3. For an n-input gate, what can be assumed about the propagation delay, d_n?	16.6%	66.6%

Table 2—Smith College CSC 270/EGR 251 Digital Circuits Class Data

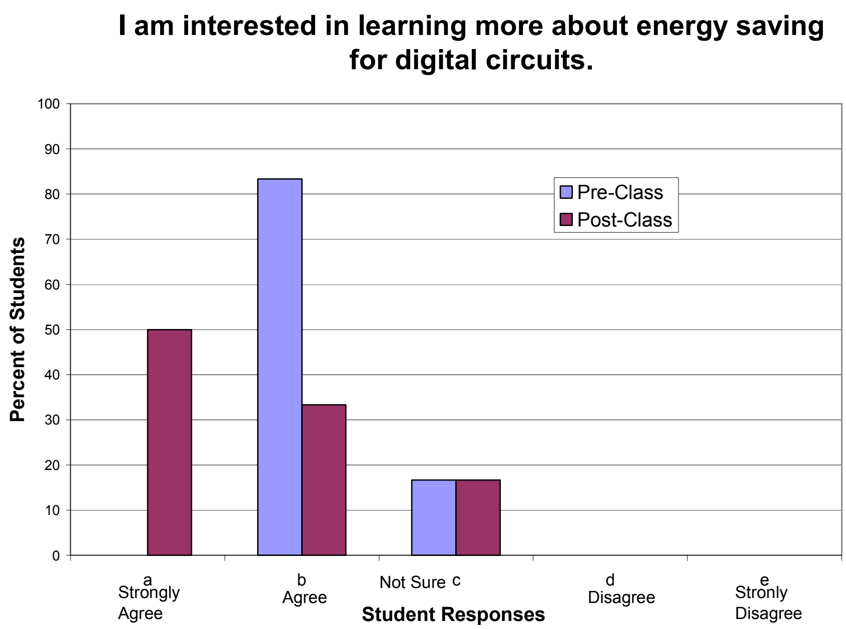

Figure 1-- Smith College survey question 4

IV. Discussion

The data collected for this study not only shows student aptitude for low power digital circuitry; it also indicates that once students begin to learn about power saving techniques, their interest in developing that knowledge increases. This may be in part because it links their studies with real world applications. This type of concrete connection has been shown specifically to draw and retain women and minorities in the field of engineering[11]. Furthermore, Goodman, et al.[26] write “the interests, socialization, and experiences of women (and other underrepresented groups) are often at odds with traditional engineering structures. These populations tend to flourish, on the other hand, in settings that emphasize hands-on, contextual, and cooperative learning.” While these strategies have been shown to be effective in targeting women and minorities, other studies show that such approaches are successful with men as well[27]. The majority of students at both UMass and Smith College in this study agree that these topics should be incorporated into the undergraduate curriculum.

It has also been shown that women are attracted to the study of engineering when they see it as being socially relevant. For example, in a study of over two thousand female engineering students, the Goodman Research Group found that one of the reasons why these women were attracted to engineering was because they saw it as a means for helping people and society[26]. However, the social relevance of engineering is not always apparent; environmental engineering is a field where students can easily see how engineering helps people and society in general and not surprisingly, this field has a significantly higher proportion of women than other areas of engineering[28]. Grasso[29] discusses this issue:

> … many college-bound students, notably women, are unwilling to sign on for educational programs that promise such a narrow role in society. Ask a physician why she selected a career in medicine and you rarely hear: "I liked biology." rather, the more common response is: "I wanted to help people." Contrast this with an engineer's most common response: "I liked math and science" and it is easy to see why many young people don't see a future in a profession perceived as isolating and lacking in social relevance. Indeed, in engineering disciplines where social relevance is manifest, such as environmental or biomedical, women are well-represented.

Mikic and Grasso[30] also note: "the view of engineering as a profession in service to humanity is becoming more widespread and thus is the inclusion of socially relevant design projects throughout the curriculum." In their project where students design toys to teach children about technology, they found that women engineering students were especially attracted by the social relevance of engineering.

Both Smith College and UMass are dedicated to diversifying this area of study. UMass has, in fact, a dedicated Minority Engineering Program (MEP), whose charter is to "improve the enrollment, retention, and successful graduation of students of African-American, Native American, Hispanic, and Cape Verdean descent in the engineering field." MEP staff actively recruits qualified minorities into the engineering program, and provide them with additional academic advising, tutoring, and a mentor program. The only women's college with an engineering program, Smith College is dedicated to providing a new approach to engineering education that encourages women to enter and remain in the field. Developing learner-centered educational modules that teach engineering for a sustainable future are completely consistent with the program's mission.

These modules will be taught using methods that have been proven to engage and stimulate the students. While some traditional techniques will be used, there will be an emphasis on the use of learner-centered pedagogy. For example, concept questions will be developed to allow students to become aware of their preconceptions and measure their learning. Project-based approaches will also be used to help students take control of their own learning and thus increase engagement[14]. Excerpts from texts and pre-designed software and hardware curriculum will be integrated into these modules to ensure the most advanced and comprehensive tools[2, 23].

V. Summary

The impact of this effort will be the following:

(1) Power-aware issues are becoming of central importance in many applications. These curriculum modules will transfer an increasingly important subdiscipline of computer systems to the undergraduate and graduate curriculum.

(2) Students will learn the value, both ethical and economic, of sustainable technologies.

(3) The project will assist in the education of women and racial minorities. This is consistent with emphasis at Smith and UMass to actively seek out under-represented minorities to enter the field of engineering.

VI. Acknowledgements

This research has been funded by the National Science Foundation.

VII. References:

1. Viredaz, M. A., L. S. Brakmo, and W. R. Hamburgen. 2003. Energy Management on Handheld Devices. *Association for Computing Machinery (ACM) Queue*. Volume 1, Number 7.

2. Conrad, J. M. and I. Howitt. 2004. Software and Hardware Tools for Teaching Communications Concepts and Introducing Students to Low-Power Wireless Communications, *Proceedings of the 2004 International Conference on Engineering Education*, Gainesville, FL.

3. Unsal, O. S. 2002. System-level power-aware computing in complex real-time and multimedia systems, Ph.D. thesis, University of Massachusetts, Amherst, MA.

4. Allenby, B., and D. Unger. 2001. Information technology impacts on the U.S. energy demand profile. *E-Vision 2000, Key Issues That Will Shape Our Energy Future: Analyses and Papers Prepared for the E-Vision 2000 Conference*, Santa Monica, CA: RAND CF-170/1-1-DOE.

5. IEEE Computer Society/ACM Task Force on Computing Curriculum, *Computing Curricula - Computer Engineering "Ironman Draft,"* June 8, 2004. Retrieved from http://www.eng.auburn.edu/ece/CCCE/

6. Academic Handbook. 2005. King Fahd University of Petroleum and Minerals, Saudi Arabia. Retrieved from http://www.kfupm.edu.sa/ee/bscourses.htm

7. University of Utah, Integrated System-Level Design in Electrical Engineering. National Science Foundation Grant Proposal EEC-0431958. Retrieved from http://www.ece.utah.edu/~cfurse/NSF/Project%20Description.htm

8. Momoh, J. A., P. Bofah, and A. Chuku. 1996. Optimizing a Design Based Undergraduate Power Engineering Education Program. *Proceedings of the Frontiers in Education (FIE) 1996 Conference,* Salt Lake City, Utah.

9. Naohiko, S. 2003. Digital Applications and Education with SFL and FPGA. *Proceedings of the 2003 Association of South-East Asian Nations (ASEAN) Microelectronics,* Manila, Philippines.

10. Kazem, S. 2004. University of Arkansas Undergraduate Student Handbook, University of Arkansas, Fayetteville, Arkansas.

11. Seymour, E., and N. M. Hewitt. 1997. Talking About Leaving. Westview Press, Boulder, CO.

12. Busch-Vishniac, I., and J. P. Jarosz. 2003. Deconstructing Engineering Education Programs to Foster Diversity. *Proceedings of the American Society for Engineering Education (ASEE) National Conference 2003*, Nashville, TN.

13. Singley, K., and J.R. Anderson. 1989. The Transfer of Cognitive Skill. Harvard University Press, Cambridge, MA.

14. National Research Council. 1999. How People Learn: Brain, Mind, Experience, and School. National Academy Press. Washington D.C..

15. Douglis, F., P. Krishnan, and B. Bershad. 1995. Adaptive Disk Spin-down Policies for Mobile Computers. *Proceedings of the Second USENIX Symposium on Mobile and Location-Independent Computing,* Ann Arbor, MI.

16. Kumar, R., K.I. Farkas, N. P. Jouppi, P. Ranganathan, and D. M. Tullsen. 2003. Single-ISA heterogeneous multi-core architectures: the potential for processor power reduction. *Proceedings of the 36th International Symposium on Microarchitecture.*

17. Lim, C. H., W. R. Daasch, and G. Cai. 2002. A thermal-aware superscalar microprocessor. *Proceedings of the International Symposium on Quality Electronic Design*, San Jose, CA.

18. Chu, W.W., L. J. Holloway, L. Min-Tsung, and K. Efe. 1980. Task Allocation in Distributed Data Processing. *IEEE Computer*, Volume 13, Number 11.

19. Yu, Y., and V. K. Prasanna. 2003. Energy-balanced task allocation for collaborative processing in networked embedded systems. *ACM SIGPLAN Notices, Proceedings of the 2003 ACM SIGPLAN Conference on Language, Compiler, and Tools for Embedded Systems (*LCTES), Volume 38 Issue 7

20. Data can be found at http://www.xbow.com/Products/WirelessSensor-Networks.htm.

21. Heinzelman, W. R., A. Chandrakasan, and H. Balakrishnan. 2000. Energy-efficient communication protocol for wireless microsensor networks. *Proceedings of the 2000 Hawaii International Conference on System Sciences,* Maui, Hawaii.

22. Shah, R., and J. Rabaey. 2002. Energy aware routing for low energy ad hoc sensor networks. *Proceedings of the 2002 IEEE Wireless Communications and Networking Conference (WCNC),* Orlando, FL.

23. Low-Power HF Microelectronics, a unified approach. Ed. Gerson A. S. Machado. Vol. 8. London: The Institution of Electrical Engineers, 1997.

24. Hui, J., Z. Ren, and B. H. Krogh. 2003. Sentry-Based Power Management in Wireless Sensor Networks. *Proceedings of the 2003 Information Processing in Sensor Networks (IPSN) Conference,* Palo Alto, CA.

25. TOSSIM simulator specification. Retrieved from http://webs.cs.berkeley.edu/tos.

26. Goodman Research Group, Inc. 2002. Final Report of the Women's Experiences in College Engineering (WECE) Project. Funded as "A Comprehensive Evaluation of Women in Engineering Programs." National Science Foundation Grant REC 9725521, Alfred P. Sloan Foundation Grant 96-10-16. Cambridge, MA.

27. Rosser, S.V. and Kelly, B. 1994. From hostile exclusion to friendly inclusion: USC System Model Project for the transformation of science and math teaching to reach women in varied campus settings. *Journal of Women and Minorities in Science and Engineering*. Volume 1, Number 1: 29-44.

28. Commission on Professionals in Science and Technology, data derived from Engineering Workforce Commission, Engineering and Technology Enrollments, Fall 2004.

29. Grasso, D. 2002. Engineering a liberal education. *American Society of Engineering Education Prism* magazine. Volume12, Number 2: 76.

30. Mikic, B and Grasso D. 2002. Socially-Relevant Design: the TOYtech project at Smith College. *Journal of Engineering Education*. Volume 91, Number 3: 319-326.