

Inquiry-Learning with WebLab: Undergraduate Attitudes and Experiences

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The Microelectronics WebLab at MIT allows students to do actual (not simulated) laboratory research on state-of-the art equipment through the Internet. This study assesses the use of WebLab in a junior-level course on microelectronic devices and circuits in 2004–05 and 2005–06. In quantitative surveys and qualitative interviews, students and faculty reported that WebLab was effective as an instrument of learning, and grew more so with refinements of the program. WebLab allowed undergraduates to learn at their own pace and on their own schedules. It enabled them to use different processes of learning (intuitive, visual, abstract), and it gave them an opportunity to link individual and collaborative effort in creative combinations. Online laboratories on this model have broad applications in the experimental sciences and in other research-oriented disciplines.

KEY WORDS: WebLab; microelectronics; engineering education; online laboratories; inquiry learning; assessment

INTRODUCTION: THE DEVELOPMENT OF WEBLAB

This inquiry began not with a theory, or a model, or a fixed hypothesis, but rather with a set of open-ended questions about student attitudes toward their own learning experiences with WebLab in an microelectronics course at MIT during the Fall and Spring semesters of 2004–05 and the Fall of 2005 (Fischer, 2005a, b; Mitchell, 2005a, b).

Opportunities for laboratory research by engineering students have been limited by the cost of equipment, limitations of space and other factors. WebLab was developed through the MIT iCampus project as a response to this problem. It has been used

in undergraduate and graduate microelectronics courses at MIT, and also in overseas programs. Since 1998, more than 3600 students on four continents have worked with it in university-level courses (MIT iCampus iLabs website, 2006).

WebLab consists of laboratory instruments for the characterization of microelectronic devices, together with computer hardware and software that make this equipment accessible to users through the World Wide Web (Figure 1).

The system is based on iLabs Shared Architecture, a design that separates online labs into modules connected by a Web service broker (Hardison *et al.*, 2005). It can accommodate a large number of users through a queuing system for access to the server and test equipment. A switching matrix allows remote selection of one of eight possible devices. The process of remote control, combined with a local database, permits flexible and efficient management of multiple users (Figure 2).

Students can use WebLab at a time and place of their choice. Accessing WebLab remotely, students perform real-time experiments and collect data about

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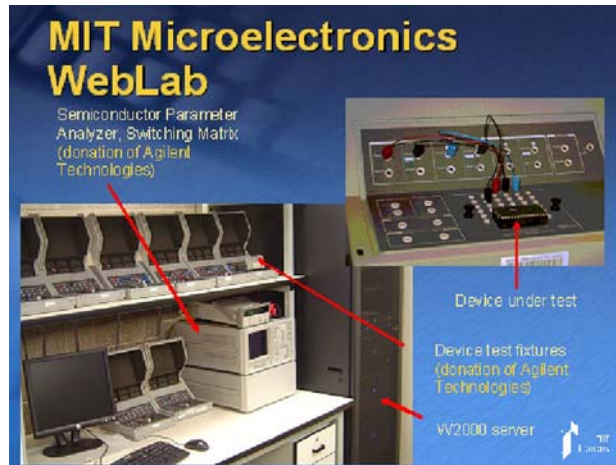


Fig. 1. WebLab hardware.

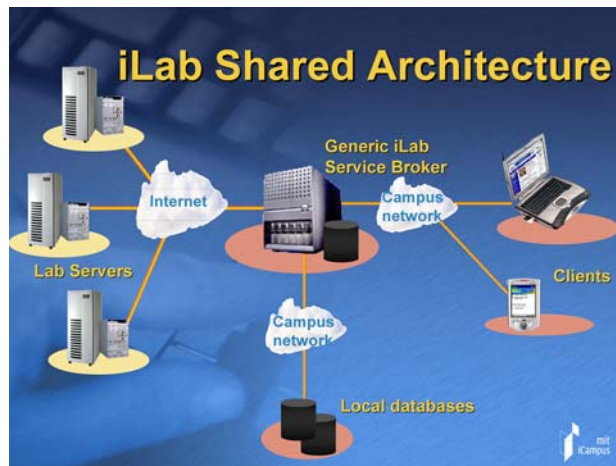


Fig. 2. iLab shared architecture.

the actual operation of real microelectronic devices. They can also compare their results with theoretical models presented in the course (del Alamo et al. 2003).

INQUIRY-LEARNING THROUGH WEBLAB

A major purpose of WebLab is to promote authentic, experiential, hands-on, inquiry-based learning. It does so through genuinely open-ended laboratory experiments, which benefit learners in ways that rarely happen in lectures, or simulated research. In a more open process of inquiry and discovery, it also helps students to learn about the learning process itself (Jeppson, 2004; Bransford et al, 2002; Dunbar, 2001; Henry, 1996).

Inquiry-learning has been a major theme in the history and philosophy of education since the work of John Dewey (1859–1952) and Jean Piaget (1896–1980). It is flourishing today in many forms and under many names, such as discovery learning, problem-solving approaches, and constructivism. Always, it centers on the active engagement of the learner in an open process of questioning and discovery. An expanding literature has abundantly documented the value of this approach. Authentic problem-solving experiences are especially helpful in science and engineering, and are also useful in most empirical disciplines (Albert, 2000; Anderson, 2002; Bruner, 1987; Felder and Brent 2003; Henry, 1996; Dewey, 1938; Feisel and Rosa, 2005; Martin-Hansen,

2002; Minstrell, 2000; National Research Council, 2000; Piaget, 1928; Prince, 2004).

WebLab is very much in this tradition. Students can use it to devise their own experiments, within the framework of a course syllabus or a curricular objective. In its microelectronic applications, it allows students to construct their own test vectors, measure current-voltage characteristics of a device, and extract specific parameters. They can also compare their own experimental data with theoretical models.

WebLab has been designed to challenge students. They are asked to design test-vectors that respond to assignments. Students must also learn to deal with issues of measurement such as range, point-distribution, and compliance. Another form of learning can be gained from the process of debugging errors in submitted test vectors. The graphical component of the WebLab interface enables students to select variables and graph results on either a linear or logarithmic scale. They can also download quantitative data, analyze it with standard software packages, and compare their results with theoretical models. That process in turn encourages reflection about non-idealities of the devices and shortcomings of the models. The flexibility of the WebLab interface allows students to follow their curiosity beyond initial assignments, to explore other questions in an independent way (Figure 3).

THE USES OF WEBLAB IN A MICROELECTRONIC COURSE

This project assesses undergraduate perceptions of the effectiveness of WebLab in a junior-level course in Microelectronic Devices and Circuits at MIT during three semesters; the spring and fall of 2004–05 and the fall of 2005–06. The purpose of the course was to teach students how to use incremental and large-signal techniques to analyze and design transistor circuits and their components. It covered the following topics: modeling of microelectronic devices, basic microelectronic circuit analysis and design, physical electronics of semiconductor junction and MOS devices, relation of electrical behavior to internal physical processes, development of circuit models, and understanding of their uses and limitations. The course syllabus and other information about the 2005–06 fall term Microelectronics course can be found at MIT OpenCourse Ware (2005).

WebLab assignments in the course asked students to work with three microelectronic devices. Two were common transistors: a MOSFET (metal-oxide semiconductor field-effect transistor) and a BJT (bipolar junction transistor). The third was a PN Diode (an electronic equivalent to a check valve). In typical WebLab experiments, students were asked to:

- collect data for a given microelectronic device, on its output, transfer or backgate characteristics
- graph observed device characteristics

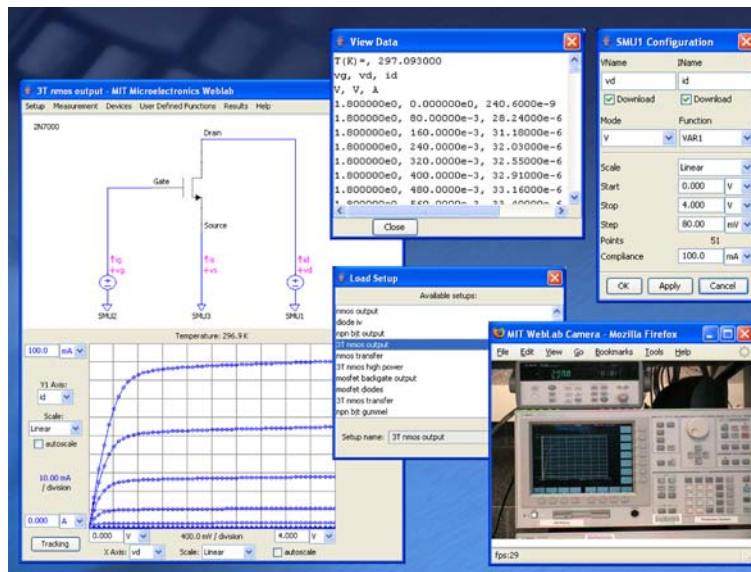


Fig. 3. Screen shots of the graphical user interface of the MIT Microelectronics WebLab.

- download and analyze data on the student’s personal computer
- extract device parameters from the data
- program a model of device operation based on equations presented in lecture
- compare real measurements with theoretical model
- measure other characteristics of interest to the student

ASSESSING WEBLAB: RESEARCH DESIGN AND METHODOLOGY

The purpose of this project was to study the process of WebLab learning as perceived by students at MIT. All were undergraduates enrolled in the same microelectronics course within the Department of Electrical Engineering and Computer Science. The research had two major components: quantitative surveys and in-depth qualitative interviews with a small number of individual students.

WebLab Surveys

The surveys were developed in the fall semester of 2004, and used in the spring semester of 2005, and again in the fall semester of 2005. At the last lecture in each semester, all students who attended were asked to complete the survey in writing. Every student who was present at the last lecture did so: 37 of 63 students enrolled in the spring semester of 2005; 33 of 63 enrolled in the fall of 2005.

The spring survey included 44 questions about the use of WebLab, the collection and analysis of data, and general assessments of Web-Lab experience. On the basis of further study in the summer of 2005, the fall survey repeated all of those questions, and added 13 others on time-commitment and work habits, for a total of 57 survey-questions. Each question framed a statement and asked students to register degrees of agreement or disagreement on a seven-point Likert scale.

For purposes of analysis, the survey answers were scaled in four groups around the following general issues: How effective was the WebLab

interface found to be for the collection of data? How did students analyze the data? How did they assess their learning experiences? How did they feel about further applications of WebLab?

To test the reliability of each scale, coefficient alphas and item-total correlations were calculated, following methods discussed by Streiner and Norman, with reliability procedures in SPSS 10.0 for MacIntosh (SPSS, 1999; Streiner and Norman, 1995; Norman and Schmidt, 1992; Schmidt et al. 1999). Alpha correlations on all four scales were robust, ranging in value from .80 to .90. Results were tabulated and compared by semester, to assess change in perceived effectiveness of WebLab. We did not analyze data by major, gender, age, or ethnicity. Our interest was in the experience of individual learning, rather than in the performance of groups.

WebLab Interviews

The second part of the assessment consisted of in-depth interviews with a small number of students in each semester (Table I). An interview protocol was developed in the fall semester of 2004, on the basis of conversations with faculty and pilot-interviews with nine students. In the spring of 2005, 27 students were selected at random and invited to be interviewed on a voluntary basis. Twelve agreed to participate. The interviews were repeated in the fall semester of 2005, when interview-requests went to 51 students (again selected at random). Of that number, 22 agreed to participate, and all were interviewed.

The interviews were held in the offices of the Teaching and Learning Laboratory at MIT. Each session was conducted individually, and recorded digitally by iPod, with the permission of the student. The median length of interviews was approximately 30 min. The range was from 25 min to more than an hour.

Interviews were guided by a set of 39 questions on individual patterns of use of WebLab, strengths and weaknesses of hardware and documentation, the

Table I. Student Interviews

	Course enrollment	# Students interviewed	Total # interviews	When interviewed		
				Mid-semester	End of semester	After end of semester
Fall 2004	63	9	9			9
Spring 2005	90	17	19	9	10	
Fall 2005	65	22	22	10	12	
Total	218	48	50	19	22	9

use of models and empirical questions processes of data collection and analysis, the use of graphs, the utility of WebLab in meeting course objectives, options for individual and collaborative study, and assessments of WebLab as a learning experience. These questions established the initial frame of each interview, but did not constrain it. The conversations ranged far beyond them in open, creative and free flowing discussions. The object was not to obtain quantitative data, which had been the purpose of the surveys. The interviews were conceived as open-ended, heuristic inquiries into individual attitudes, experiences, and judgments. One goal was to deepen understanding of empirical results in the surveys. Another was to explore creative possibilities for the refinement of WebLab in the present, and the development of WebLab in the future.

STUDENT RESPONSES: PROBLEMS OF ACCESS TO WEBLAB

In surveys and interviews during the first and second semesters during the fall and spring of 2004–05, undergraduates had mixed opinions about the accessibility of WebLab. They described it in general as “user friendly,” “cool,” “neat,” or “fun.” These judgments were tempered by reports of specific problems with the WebLab interface. In the spring semester of 2005, students found the program documentation to be insufficient to their needs. Some couldn’t find it. Others thought it was flawed. They complained that the server failed in periods of very heavy demand, especially during the spring semester of 2005. A rescheduling of the second WebLab

assignment to the last week in the term left students with a feeling of frustration at end of the course. These problems had an impact on quantitative evaluations in the WebLab Survey.

Based on assessments of WebLab in the 2004 fall and 2005 spring semesters, many changes were introduced in the summer of 2005. The documentation was overhauled and the manual was rewritten. On-line tutorials were developed, and a class tutorial session was added at the beginning of the semester. FAQs (frequently asked questions) were added and posted on the website. A number of small bugs were identified and fixed. Large WebLab assignments were divided into a larger number of more specific assignments, which were distributed with care through the semester. Demonstrations of WebLab and device characteristics were added to lectures (del Alamo, informal conversations [2005–2006]; MIT OpenCourseWare, 2005).

These changes improved the operation and effectiveness of WebLab. During the third semester in the fall of 2005, students reported that WebLab ran more smoothly. Documentation was more clear, and also more accessible. Students reported fewer technical problems, and they were progressively more positive about the experience. No one who was interviewed in the 2005 Fall semester reported difficulty in accessing WebLab. Many found the program so clear they used the documentation rarely, if at all. One student said, “When it’s time to do the WebLab, you just connect it [and begin.]” Surveys indicted that these positive assessments increased with time.

A related change occurred in the number of assignments (Table II). WebLab can be used at many

Table II. WebLab Assignments in Three Semesters

Week due	Content	WebLab % of assignment	WebLab % of final course grade
<i>Fall Semester 2004</i>			
7	MOSFET characterization	100	10
Total			10
<i>Spring Semester 2005</i>			
2	PN diode characterization	100	5
13	Device characterization and circuit design project	50	2.5
Total			7.5
<i>Fall Semester 2005</i>			
2	PN diode characterization	40	1.1
3	PN diode characterization (cont.)	40	1.1
4	PN diode characterization (cont.)	10	1.3
6	MOSFET characterization	50	1.4
7	MOSFET characterization (cont.)	45	1.3
10	BJT characterization	50	1.4
Total			6.5

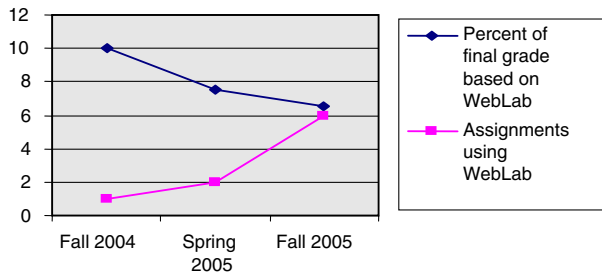


Fig. 4. Number of assignments using WebLab and percent of final grade based on WebLab.

different levels of frequency and intensity. In the first semester studied here (fall 2004), students completed only one WebLab project near the middle of the semester (the seventh of thirteen weeks). In the second semester (spring 2005) there were two projects, one near the beginning, and the other near the end of the semester. During the third semester (fall 2005) students used WebLab six times, nearly two-thirds of the homework assignments.

In successive semesters, the use of WebLab also increased as a proportion of homework assignments and projects, and declined as a percent of final grades (Figure 4).

The impact of technical improvements appears in student responses to the WebLab Survey (Table III). Rankings on WebLab user-friendliness, clarity, and coherence of data presentation were substantially higher in the fall 2005 semester than in the previous semester. Students agreed more strongly

that controlling the WebLab remotely from a PC did not interfere with their learning. Bugs in the WebLab were viewed as less frustrating (Table III).

Students liked being able to choose when and where to use WebLab. They preferred to work primarily on their own computers. Students also used computer clusters on campus. Only one student in the fall semester reported that he worked all of the time with another student in a computer cluster. Other students reported that they worked with other students at computer clusters, especially when confused by part of the assignment, or wanting to verify their results.

Working remotely was not difficult for them. In each semester students commented about the importance of being able to work with real devices used by professional engineers, rather than using computer simulations. They found data collection efficient and easy, and commented about the time it saved them in their busy schedules. One student noted that “WebLab did in minutes what would take hours by hand.”

Students in both courses found WebLab to be a new sort of hands-on lab experience. One student said, “It’s a neat way to do experiments without having to toil over the wiring and complications.” Students noted that WebLab was quite different from other laboratory work. One noted the importance of actual inquiry experience. He wrote, “WebLab is a good opportunity to teach people how to do good analysis, which I think is important because you don’t get that experience with regular problem sets.”

Table III. Self-Reported Student Experience with the Use of the WebLab

Degree of agreement or disagreement to the following statements about WebLab	Spring 2005			Fall 2005			%Change
	Mean	SD	<i>n</i>	Mean	SD	<i>n</i>	
WebLab is user friendly ^a	3.78	1.51	36	5.18	0.95	33	+37.04
WebLab documentation is clear and effective ^b	2.95	1.74	36	4.45	1.39	33	+50.85
The graphical interface enhances the learning experience ^c	4.08	1.64	36	5.76	1.06	33	+41.17
The graphical interface presents data in a clear and coherent manner ^d	4.39	1.61	36	5.58	0.90	33	+27.10
Controlling WebLab remotely from a PC does not interfere with my learning	4.76	1.66	36	6.03	1.16	33	+26.68
The bugs in the WebLab make the lab a frustrating experience ^e	3.95	1.52	36	3.09	1.68	33	-12.30

Student survey responses, ranked on a 7-point Likert scale, ranging from “1” (= strongly disagree) to “7” (= strongly agree). Intervening values have no descriptors.

^a In the spring of 2005, this question was worded differently: “I found the WebLab user friendly.”

^b In the spring of 2005, this question was worded differently: “The WebLab documentation was well designed.”

^c In the spring of 2005, this question was worded differently: “The graphical interface provided an effective experience.”

^d In the spring of 2005, this question was worded differently: “The graphical interface presented data in a coherent manner.”

^e In the spring of 2005, this question was worded differently: “I found the bugs in the WebLab frustrating.”

Table IV. Self-Reported Student Learning Behavior

	Fall 2005		
	Mean	SD	<i>n</i>
How well do the following phrases describe the mental operation used while gathering data when running the WebLab Experiments?			
Visualizing how devices work	4.33	1.27	33
Reasoning about the behavior of devices	4.91	1.28	33
Applying concepts discussed in lecture or readings	4.82	1.38	33
Thinking about relationships among the variables	5.12	1.34	33
How well do the following phrases describe the mental operations used completing the data analysis?			
Visualizing how devices work	4.56	1.56	32
Using intuition to understand devices	4.78	1.52	32
Formulating concepts about the behavior of devices	4.81	1.38	32
Thinking about relationships among variables	5.41	1.32	32
Thinking about how the lab experiences relate to material previously learned	4.88	1.34	32

Student survey responses, ranked on a 7-point Likert scale, ranging from “1” (= poorly) to “7” (= extremely well). Intervening values have no descriptors

USING WEBLAB: DATA GATHERING AND ANALYSIS

WebLab assignments typically included two tasks: data gathering and data analysis (Table IV). The students reported that collection of data was simple and easy. They worked alone on this step, and could do it quickly, although students occasionally had long waits for data retrieval, typically on the night before the assignment was due. “It’s pretty quick to get the right data, and it’s ‘output-ed’ in a nice convenient form,” said one student.

Data analysis was the next stage. Students applied concepts discussed in lecture, formulated concepts about the behavior of the devices, examined relationships among variables, and considered how lab experiences related to material that they had previously learned. They found that the task of analysis was straightforward, and were helped by clear instructions, but those who were pressed for time complained that the analytic process was “tedious.”

Even as most students worked alone at their computers for the collection of data, they also collaborated with others on particular tasks, such as sharing questions, exchanging ideas and exploring possible solutions. One student said, “Once I’d collected the data, I worked with others trying to figure out what to do with it.” Another commented that “after being stuck for a while, I’d ask one of my friends.” A third noted, “Occasionally I’d look at someone else’s work just to make sure the graphs looked right...sanity check, mostly.”

In these various ways, students agreed the importance of collaboration to their own learning.

One noted that others could “help catch mistakes that you’d made,” or “explain something you didn’t get the first time around.” Another considered “collaborative work absolutely mandatory, with a very clear correlation to doing well in a course.” A third agreed that “two heads are better than one.”

In both interviews and surveys, students observed that WebLab provided opportunities to develop skills of critical and creative thinking. One student said, “I definitely took stuff away from WebLab I couldn’t have taken away from just problems. In other problems in the assignment it seemed like you found the right formula to match the problem, plug in the numbers and got the solution. With WebLab you actually thought about the problem and how to set it up.” Another student commented, “Even when I was working on one of the problems not requiring WebLab, I could approach the problem in a more logical way, because I already had a picture of the sort of graph to expect.”

The graphs generated by the program were thought to be especially helpful as aids to analysis (Figure 5). Everyone liked the WebLab graphing feature, calling it “absolutely necessary,” “the best part,” and “very valuable.” Several students commented that “a picture is worth a thousand words,” and one added, “And that’s very true, even in things that are so mathematical.” Others thought the graphs helped them to learn if they were on the right track or not, and to see if their data was in the right range.

Students used their graphs in an interesting variety of ways. For one student graphs helped to “capture the image in my mind.” Another student said, “Graphing was useful because you could

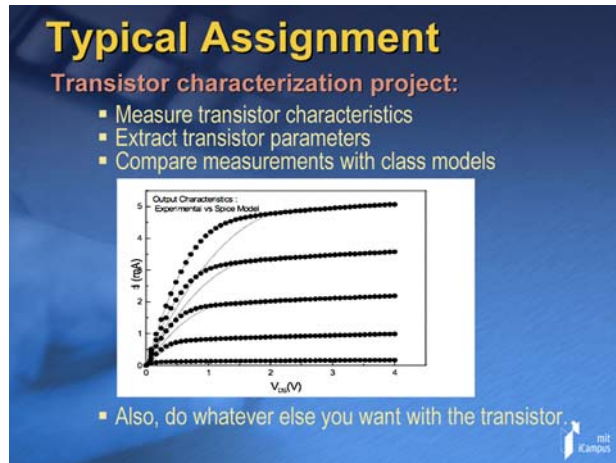


Fig. 5. Comparison of measured and modeled current-voltage characteristics of a MOSFET as provided by a student.

visualize difference between components. The best part was that you could visualize those relationships.” One student reported that to him “holding things in my head visually is second nature.” Others worked in different ways. One described himself as a “numbers person rather than a visual learner.” He continued, “If I had a choice between graphs and numbers I would always pick a formula.” At the same time he noted that “visual images help develop an intuitive sense.”

The graphs also helped students understand the behavior of various devices in yet other ways. One said that “WebLab showed the behavior of real devices and the difference between the real devices and the ideal model.” Another thought that “the graphs help you get a feel about how a device is going to behave.” A third noted that “A lot of learning happens because you see how things fit together and what needs to be adjusted.”

The students spoke at length about the importance of WebLab’s graphing capabilities in the development of intuitive understanding of microelectronics. For some, visual images became an intuitive shorthand for important relationships and ideas. One student mentioned that intuition was stressed in the course. He said, “WebLab graphic images helped develop an intuitive sense more than any other part of the course.” Another noted that graphic images helped him to “think more intuitively,” while a third said that WebLab “solidifies an intuitive understanding of what’s happening.” One student wasn’t sure that WebLab helped him “learn the material per se, but at the very least it’s good for gaining intuition. Often times I think that’s more

useful than strictly learning material anyway.” Others used this part of the program differently. “WebLab graphs help me,” commented another student. “I try to think about it conceptually—what would change if I did this. I would change a parameter and make a new graph to see how the variable changes.”

LEARNING WITH WEBLAB: UNDERSTANDING CONCEPTS IN MICROELECTRONICS

In the language of the course syllabus, students were expected by the end of the term to be able to:

- Explain and apply basic concepts of semiconductor physics relevant to devices.
- Describe, explain, and analyze the operation of important semiconductor devices in terms of their physical structure.
- Explain describe, and use physics-based models of varying levels of complexity, select models appropriate to a specific need, and apply those models to analyze multi-component circuits.
- Analyze and design microelectronic circuits for linear amplifier and digital applications.
- Confront integrated device and/or circuit design problems, identify the design issues, and develop solutions. Overall, students were confident that they had reached these goals. They felt that they had gained an understanding of basic microelectronic principles. They believed that they had mastered the operation of semiconductor devices, and their underlying physics. They also felt they had enlarged their intuitive understanding of microelectronics. WebLab augmented what students gained from lectures and the textbook, providing another perspective on the learning process. The students spoke about the ways in which WebLab helped them increase their understanding of basic microelectronic concepts. They commented that WebLab “helped to conceptualize things,” encouraged them to “build concepts in the mind,” and made it possible “to confirm concepts learned in class.”

This perception was reinforced by another factor. One student added, “WebLab builds confidence, and even enthusiasm for learning and understanding the subject.” This growing sense of confidence from hands-on research was itself an important part of the learning process.

That sort of confidence permitted students to approach their work in a more open and creative way. Some took a playful approach, and were delighted in learning from their own inquiries. One student said, “It was kind of cool just to play around with actual numbers, actual data.” Another added, “What you can do is play around with inputs and figure out why they often differ so much.” He went on to note, “It gives you a good overall view. It’s more intuitive than just the numbers.”

Quantitative results of the WebLab Survey confirmed what students said in interviews. Students strongly agreed that WebLab helped them understand the behavior of the devices, how to characterize a device) and also helped them understand the differences between theory and application. They also agreed that WebLab helped them develop a “feel” for how microelectronic devices work, and deepened their understanding of related lectures and readings in the course (Table V).

These responses grew stronger from one semester to the next. In both semesters, students believed that the use of WebLab, in combination with the more traditional methods of lectures, texts and tests, had enlarged and enriched their opportunities for learning. They also felt that they had come to understand the behavior of semiconductor devices, and had mastered the equations that can be used to compare with theoretical models. They commented that WebLab “helped to conceptualize things,” encouraged them to “build concepts in the mind,” and made it possible “to confirm concepts learned in class.” The

strength of these judgments increased from one semester to the next, with the improvements that were made in the WebLab program.

OVERALL STUDENT ASSESSMENTS OF WEBLAB EXPERIENCE

WebLab Surveys in the spring of 2004–05 and the fall of 2005 included sections in which students were asked to rate their experience of WebLab in general terms. Here again, the results showed a clear pattern of improvement from one semester to the next (Table VI).

Students found the revised programs to be more “effective,” more “interesting,” and more “stimulating.” Larger gains appeared in the strength of perceptions that WebLab was more “enjoyable,” more “meaningful,” and more “exciting.” The linkage of these responses suggested that as WebLab became more effective, students were in their own words, more “excited” by work that was more “meaningful” and more “enjoyable.”

At the same time, negative judgments grew weaker. As the WebLab system worked better, students were less likely to find the experience “tedious,” “frustrating,” “stressful” and “discouraging.” As this happened they were less likely to blame themselves for learning problems. In the first semester, when the WebLab was not working as well as it did later, students remarked in their interviews that they were overwhelmed by the current workload, and failed to give themselves enough time to do a good job, and were too tired to learn much from their work with WebLab. Structural problems in WebLab created a sense of failure in students, and they blamed themselves.

After the problems were corrected, students believed that they had done better job in planning

Table V. Self-Reported Student Perceptions of the Effects of WebLab on Understanding

How well the WebLab experience affected understanding in particular areas	Spring 2005			Fall 2005			%Change
	Mean	SD	<i>n</i>	Mean	SD	<i>n</i>	
Behavior of the devices	4.30	1.73	37	5.42	1.17	33	+ 26.05
How to characterize a device				5.45	1.15	33	
Differences between theory & application	4.22	1.49	37	5.55	1.03	33	+ 31.10
Developing intuitive sense on how devices work ^a	3.81	1.66	37	5.00	1.20	33	+ 31.23
Related lectures and assigned readings	3.62	1.52	37	4.82	0.88	33	+ 33.15

Student survey responses, ranked on a 7-point Likert scale, ranging from “1” (= poorly) to “7” (= extremely well). Intervening values have no descriptors.

^a In the spring of 2005, this question was worded differently: “Developing an intuitive feel of how to model.”

Table VI. Self-Reported Student Opinions about the Overall WebLab Experience

	Spring 2005			Fall 2005			%Change
	Mean	SD	<i>n</i>	Mean	SD	<i>n</i>	
Degree of Agreement with descriptors of the overall WebLab experience							
Meaningful	3.82	1.59	34	5.18	1.10	33	+ 35.61
Effective	4.12	1.57	34	4.79	1.22	33	+ 16.26
Interesting	3.56	1.38	34	4.67	1.36	33	+ 31.18
Stimulating	3.43	1.38	34	4.09	1.20	32	+ 19.24
Enjoyable	3.03	1.29	34	4.00	1.17	33	+ 32.02
Exciting	3.00	1.41	34	3.63	1.29	32	+ 55.67
Tedious	5.69	1.39	34	4.00	1.60	33	âˆ’29.70
Frustrating	5.51	1.27	34	3.56	1.63	32	âˆ’35.40
Stressful	5.43	1.34	34	3.38	1.64	32	âˆ’37.76
Discouraging	4.85	1.58	34	2.75	1.37	32	âˆ’43.30
Degree of agreement with statements about the overall WebLab experience							
Overall, WebLab was a positive learning experience ^a	3.54	1.50	35	5.48	1.15	33	+ 54.80
Including WebLab examples in lecture was effective	2.97	1.34	35	5.64	1.34	33	+ 52.66
I did not give myself enough time to do a good job on the project	4.43	1.87	35	3.56	1.82	33	âˆ’19.60
I was too tired to learn much from the WebLab project.	4.51	1.74	35	3.94	1.59	33	âˆ’12.64
A key objective for the WebLab project was simply to get it done because I was so overwhelmed by the current workload.	5.83	1.32	35	4.74	1.85	33	âˆ’18.70

^a In the spring of 2005, this question was worded differently: “I found the WebLab project an effective learning experience.”

their work, and had given themselves enough time to get it done, and succeeded in doing so without being overwhelmed or exhausted. This result is very instructive, and also very hopeful in its evidence that correctable flaws in the learning process can do serious injury not only to what is learned, but also to the self-esteem of the learner, and to the possibility of learning in the future.

INFORMAL JUDGMENTS BY FACULTY AND TEACHING ASSISTANTS

One-on-one discussions were also held with three faculty members and four teaching assistants who had used WebLab in their teaching. These conversations were very informal and wide ranging, on questions about faculty experiences, approaches to Web Lab, and perceptions of its strengths and weaknesses. The conversations were held in their offices and were not recorded. The numbers were too small to be quantified, but the discussions were very interesting and suggestive.

In general, assessments of WebLab by faculty and teaching assistants were very similar to those of undergraduates. All teachers were positive about

WebLab and judged it to be a valuable and useful experience for students. Most observed that WebLab could be used by students when and where they wanted. One instructor thought that WebLab could be introduced in places where hands-on labs would be difficult or impossible. Another mentioned how important it was for students to be able to work remotely with confidence.

Faculty-members also thought another strength of the program was to be found in its efficient use of time and effort by students and instructors alike. One instructor described WebLab as “80 percent of the experience for 20 percent of the effort.” Another observed that WebLab “takes the hassle out of a lab.” Several commented on time wasted in labs because of faulty or broken equipment. With WebLab, they found that students had more time to think about learning; faculty had more time to think about teaching.

WebLab was seen as a highly effective way for students to have direct experience with real devices; a chance to play around and explore them; to make actual measurements in experimental settings, and to characterize devices. According to one instructor, “you can’t actually characterize devices in any other

way.” Another observed that students all began from a level playing field, measured the same thing, and went about the procedures in the same way.

From the faculty perspective WebLab had an important impact on student-learning. “Students learn best by doing,” was one instructor’s comment. Another noted that students mastered a new computer program, learned to characterize devices, compare them to theoretical models. According to one instructor, most students succeeded in learning what they needed to learn with WebLab. Some students got it very quickly, a few never did. Others were sure that students had gained a greater understanding of basic concepts, although the evidence was somewhat indirect.

WebLab graphic and visual images were mentioned as a particularly important way of working with ideas. One instructor observed that graphs were more important than numbers. Another thought WebLab probably helped students’ intuitive understanding, but cautioned that the evidence was limited. A third commented that “it takes experience to get an intuitive feel,” but he thought that in time students would develop a more robust intuitive understanding of microelectronics.

Instructors also commented that some students had a limited understanding of WebLab. Several said they were not sure that all the students believed they were testing real devices. Students occasionally asked, “Are we actually testing real devices? Is this real data?” Several were not sure that all students understood what WebLab offered to them in terms of developing an understanding of the “big ideas” in microelectronics. One said that students might appreciate WebLab more if they knew how frustrating it would be to do the same thing without WebLab. Another added that students often don’t realize until later what they have gained from WebLab. Instructors also commented that students’ opinions on WebLab varied; some liked it, others didn’t. One thought that WebLab fitted the learning styles of some students better than others.

They reported that some students got stuck on minor problems, or made stupid mistakes, or didn’t read the instructions carefully. One instructor observed that these problems could be corrected quickly by briefly working alongside a student on a computer. Several mentioned that some students were fearful that their mistakes would blow out a device, or cause the program to shut down. One instructor observed that students also worried about peripheral problems, which to them weren’t peripheral at all.

Another instructor noted that fear itself may have been the biggest barrier to learning.

Instructors also commented that some students seemed entirely centered on getting the right answer, and did not think about what they were learning. A few students were very annoyed when they could not figure out quickly what to do. Instead of thinking about a solution by themselves, they immediately asked instructors for answers to each specific problem. To some instructors, this suggested that some students were working for grades rather than for understanding. Overall, Faculty observed that WebLab is useful and important in what it offers teachers as well as students. This inquiry indicates that WebLab worked well for both groups.

Overall, students and faculty agreed that the more WebLab was used, the better it functioned, and the more effective it became as a way of helping students to learn. It enabled them to develop their own learning processes within a rigorous empirical discipline. And its success in these ways helped students to become more confident and more positive about their own learning. In all of these strengths, WebLab can be applied throughout the natural sciences and other experimental disciplines. Few innovations are as promising as WebLab for inquiry-based learning.

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