Lab-in-a-Box: Experiments in Electronic Circuits That Support Introductory Courses for Electrical and Computer Engineers

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Abstract:

The objective of Lab-in-a-Box is to give the student hands-on experience with wiring and analyzing simple circuits, but in such a way as to allow the experiments to be performed at home or at a study table with simple, relatively inexpensive, student-owned equipment rather than in a traditional university laboratory. Each experiment is designed to be performed using a breadboard, resistors, capacitors, inductors, transformers, and op amps. Some measurements are made with a digital multimeter, while signal traces for time-varying signals (transients) are observed using software that allows the students to convert a PC equipped with a sound card into a simple oscilloscope. Student responses to survey questions following the first implementation of the concept are very positive, thus encouraging the authors to further develop the concept.

Introduction:

An introduction to electric circuit theory and analysis lies at the foundation of electrical and computer engineering and is one of the first courses taught in the curriculum. In about half of the programs at major universities this subject is covered in a single-semester course, while in the other half it is presented in a two-semester course. Regardless of duration, in only a few schools is there an accompanying laboratory course. This is, no doubt, a result of the trend for compression of the curriculum, the large number of students, and the very high cost of equipping and staffing the requisite laboratories.

Apart from the debate about the duration of the introductory circuits course, there is also a great divergence of opinion concerning the proper time to introduce modeling languages and programs such as PSpice and MatLab into an EE/CpE curriculum. Under the auspices of an NSF-sponsored department-level review (DLR) grant[1], our department has recently given a great deal of consideration to these questions. One outcome of this review has been a complete restructuring of our introductory circuits offerings[2].

It is well-documented that students have a wide range of learning styles[3,4]. Engineering students are no different. Felder and Smith have developed a taxonomy of these learning styles[5] while Felder has compared this taxonomy to three other common descriptions including the Myers-Briggs Type Indicators (MBTI), the Kolb taxonomy, and the Hermann Brain Dominance Instrument (HBDI) [6]. Of particular significance is research on gender and ethnicity differences in learning styles where it has been clearly demonstrated that, at least in the sciences, technology, engineering, and mathematics (STEM), women are generally more visual learners than are men[7,8]. Hands-on experience greatly enhances the learning experience for all students, but is generally more important for women and minorities than for white males. It is clear that most people learn by doing [9,10]. These observations are in contradiction to the usual methods of teaching introductory circuits courses which are traditionally analytical courses. The problem thus arises as to how one may introduce a hands-on experience in these courses without incurring the very high cost of facilities, equipment and personnel.

Lab-in-a-Box, a concept that originated with the ECE Department at the University of Washington and generously shared with Virginia Tech[11], has been developed to overcome this problem and assist students enrolled in their first course in electric circuits gain hands-on experience creating and measuring simple DC circuits. Each experiment is designed to be performed as a homework problem using a breadboard, resistors, capacitors, inductors, transformers, and op amps. Some measurements are made with a digital multimeter, while signal traces for time-varying signals (transients) are observed using a program that allows the students to convert PCs equipped with sound cards into simple oscilloscopes. All work can be performed by the students at home or at a study break table using student-owned equipment; no dedicated laboratory space or university-owned equipment is required.

Lab Kits:

Lab-in-a-Box requires the following generic materials and supplies:

- A breadboard and power supply (a digital/analog “training kit”)
- A digital multimeter (DMM)
- A tool kit that includes a wire cutter and stripper, a screw driver, and needle-nose pliers.
- A laptop PC with sound card[12]
- TrueRTA™ software oscilloscope
- A wire kit consisting of spools of six different colors of wire
- A resistor kit consisting of 5 each of 72 different resistors varying from 1 Ω to 1MΩ
- A kit of components that includes resistors, capacitors, inductors, LEDs, transformers, batteries, and battery connectors

All components are available from Electronix Express[13]. Typical costs for the items are: digital trainer–$90; DMM–$27; toolkit–$5; TrueRTA–$0; wire kit–$4, and resistor kit–$6. We have selected the components such that the first seven items may be used in three additional courses: ECE 2504—Introduction to Computer Engineering; ECE 3004—AC Circuit Analysis; and ECE 3504—Digital Design I. Only a different component kit is required for each of these courses. This course-specific bag of parts varies from $10 to $19 for each of the four courses. The cost of Lab-in-a-Box amortized over the four courses is about $45 per course.

This set of components is significantly more sophisticated and expensive than the simple, unpowered breadboard used in the original University of Washington Lab-in-a-Box kit that serves only a single circuits course at a cost of about $26[14]. Our faculty believes that our increased cost is reasonable given that it allows the introduction of significantly more complex and interesting experiments into each of four courses and yet minimizes the total cost of ownership to the student. As will be seen in the Assessment section, our students agree.

Experiments:

The laboratory manual[15] starts with a section describing the use of the training kit, how to wire a breadboard, how to use the DMM, and how to install and use TrueRTA. We have developed a set of wiring guidelines that are common to all four courses where the trainer is used. This uniformity of wiring standards assures that students get a consistent message regarding the importance of learning and using good breadboard wiring techniques. This section is followed by detailed descriptions of the various experiments to be performed.

Each experiment follows a standard layout. Following a brief statement of the objectives of the experiment and the estimated time for completion (most experiments can be accomplished in approximately 20 to 40 minutes), there is background information and a list of references to set the proper perspective for the experiment. There may be a section containing information unique to each experiment, especially if such information is not usually found in the textbook. Students are required to model each experiment either analytically or, in some cases, in PSpice, so that they are sure to understand the results they should obtain experimentally. This is followed by a list of materials and supplies and a description of the experimental procedure. A page, suitable for submission with other homework problems, is provided for student calculations and experimental results. Questions concerning the agreement of experiment with theory or PSpice models are asked. Finally, an answer key with typical results is provided for the instructor. Detailed descriptions of each experiment may be found in the laboratory manual.

The experiments follow the presentation of several standard introductory electric circuit texts such as Alexander and Sadiku[16] or Nilsson and Reidel[17] to name but two. Following two experiments in which the student is introduced to the breadboard, its wiring diagram, and its internal resistances (Experiment 1A), and to the tolerances of real components (Experiment 1B), there are two experiments on basic circuit laws (Experiment 2A—Ohm's law and Experiment 2B—Kirchhoff's laws). The student then performs three experiments on series and parallel resistors and the voltage and current divider (Experiment 2C), on delta-to-wye transformations (Experiment 2D), and on mesh currents, node voltages, superposition, and the Thévenin equivalent (Experiment 2E). Following these introductory circuit experiments, the students build two op amp circuits, one with an inverting amplifier (Experiment 3A) and one with a non-inverting amplifier (Experiment 3B). The next experiments (Experiments 4A and 4B) illustrate RC and RL circuits and introduce the student to the software oscilloscope. Rise and fall times of the signals are emphasized by using a low-frequency clock signal. The natural response of an RC circuit is illustrated by turning an LED off (Experiment 4C). First order circuits are illustrated by both a differentiator circuit (Experiment 5A) and an integrator circuit (Experiment 5B). The homework experiments conclude with two introductory design projects, either of which can be used to conclude the course. The first is a project in which the student uses a number of resistors and an LED bar graph to design a simple graphical voltmeter. The second project uses LEDs, resistors, and capacitors to design a simple blinking arrow similar to one often seen as a safety warning for highway construction. Unlike the homework experiments in which a predefined circuit is built and measured, in these experiments only a component list and some hints are given for creating a circuit that must meet the project specifications.

One of the great virtues of the Lab-in-a-Box concept is its flexibility and adaptability. Depending on future use in other courses, the investment in the basic breadboard and power supply can vary from a minimal system costing only a few dollars (such as that used at the University of Washington where the package is used in a single course) in which only the smallest breadboard is used and it is powered with 1.5 V AA and 9 V batteries, all the way to a rather elegant prototyping system such as the Electronix Express Model PAD-234 Digital/Analog Trainer with fixed and variable power supplies, a sine, square, and triangular function generator, buffered LED indicators, toggle switches, and debounced momentary switches, all mounted in a plastic carrying case and costing around $110. There are systems with even more capabilities such as the LD-2 Pencilbox from E&L. Clearly, the possibilities for homework experiments are almost limitless.

Assessment:

The prototype of Lab-in-a-Box was tested in one of two equal-sized sections of ECE 2004, our introductory circuits course during the Fall 2004 semester. This three-credit course was taught using Alexander and Sadiku[16] as the text. An average of six homework problems was assigned from the text each week. Each of the twelve Lab-in-a-Box experiments described above was also assigned immediately after the appropriate background material was taught from the text. In addition, the students were introduced to the elements of PSpice modeling using the text by Tront[18]. At the end of the semester, the students were asked to complete an on-line survey of their experiences. The response was 53 out of 57 or 93% of the students who completed the course. The survey had both quantitative and free-form questions. In this section, we present some of the results from this survey.

The demographics of the class were as follows: there were 40 EEs, 9 CpEs, and 4 double majors. Thirty-seven had either completed (14) or were co-registered (23) in the required ECE 2504 — Introduction to Computer Engineering course that uses the same training kit for home digital logic experiments as was used in the course described here. The students were rather accurate in their grade expectations for the course (8 anticipated A, 28 B, 15 C, and 1 D; no one anticipated failing the course.)

Responses to some of the more quantitative questions concerning the general concept of Lab-in-a-Box are as follows:

- The completion of Lab-in-a-Box enhanced my learning of ECE 2004 material.
  SA=23%; A=51%; D=26%; SD=0%
- The Lab-in-a-Box experiments were
  too simple (0%); too complex (25%); of about the right complexity for the material covered (75%)
- The number of Lab-in-a-Box experiments was
  too few (0%); about right (68%); too many (32%)
- When compared to the number of analytical homework problems, the number of Lab-in-a-Box experiments is
  too few (6%); about right (68%); too many (26%)
- Lab-in-a-Box should be continued in future semesters in ECE 2004
  SA (26%); A (57%); D (13%) SD (4%)

In the above table, SA = strongly agree, A = agree, D = disagree, and SD = strongly disagree.

The question “In your opinion, what are the primary strengths of Lab-in-a-Box as it was used in ECE 2004?” elicited some very thoughtful comments, a sample of which is quoted below.

> “Building circuits and analyzing circuits are two completely different things, and without Lab-in-a-Box we would be much less experienced with hands-on things. It was a great way to get hands on with circuits as it is very interesting and one of the more fun things about electrical engineering.”
>
> “It helps the student better understand the concepts being discussed throughout the lectures. It gives you a ‘hands-on’ approach to the ideas being discussed in class, and gives you a head start in the understanding of electrical circuits for future classes.”
>
> “Lab-in-a-Box was helpful in that it gives the student a hands-on understanding of the course material. It can be hard to solve problems involving capacitors and op amps if you don’t understand what they look like or how to use them in the real world.”
>
> “The real world application of learned concepts better reinforced the ideas and made them more memorable and meaningful. Also allowed me to play around with layouts to test ideas and answer some circuits questions I had.”
>
> “Reinforced the material, helped perform physics labs, will probably help us for electronics lab. Also, it was interesting and more fun than analytical homework when the experiments worked.”
>
> “Lab-in-a-Box was a good hands-on method of showing how the materials we used in class applied to the real life. They also make the material interesting and motivate the student to learn and work with the material. I think it is very beneficial to the learning process in general.”
>
> “It proved the concepts in the textbook are real.”
>
> “It provides the hands-on experience that most ECE students seem not to have. I fielded many questions about Lab-in-a-Box (I have some experience building circuits) and most of the questions were very basic, e.g., how do I measure current through a circuit element.”
>
> “The primary strengths of Lab-in-a-Box are that it helped me to recognize what the actual elements were that we analyzed in our homework problems and it also helped me to visualize how the elements actually worked in a real circuit. If it weren’t for these experiments, I would not have a full understanding as to how resistors, capacitors, and inductors (for example) actually are connected to form a circuit.”
>
> “I took this class last year and until lab in the box, the items being discussed were just symbols on a drawn circuit. Now I can somewhat visualize what the physical circuit may look like and actually see what is going on instead of taking my professors word for it.”

A similar question concerning the primary disadvantages of Lab-in-a-Box was also asked. All responses to this questions concerned the usual start-up glitches involving typographical errors in the manual, mismatches between the components listed in the experimental write-ups and the actual parts provided in the lab kits, etc. The students were very good about providing errata lists and we are currently updating the lab manual for the coming semester to correct the identified deficiencies. More importantly, there was not a single negative comment about the concept of Lab-in-a-Box.

One concern that developed during the semester and which was addressed in the questionnaire involved potential damage to the input of the PC sound card if a student were to inadvertently wire an inappropriate circuit. Although 11% of the respondents strongly agreed and 49% agreed that the software oscilloscope was an important component of Lab-in-a-Box, 30% strongly agreed and 42% agreed that a hardware buffer, either in the form of a circuit included in the breadboard or as an add-on USB card, should be provided to isolate their PC from the Lab-in-a-Box experiments. This is being further investigated as we develop a new breadboard trainer that will be used starting in Fall 2005. Based on the very positive response to the question concerning the perceived value of Lab-in-a-Box, within reason the cost of the necessary hardware does not appear to be a significant issue (see below).

With regard to the digital multimeter, 79% of the students strongly agreed and 19% agreed that it was a useful/essential component of Lab-in-a-Box. Importantly, 72% of the students strongly agreed and 26% agreed with the statements that the DMM recommended by the instructor was appropriate for the course, was a good value, and should be used in future.

Finally, it was pointed out to the students that "Starting in Fall 2005, all ECE students will be required to purchase their own breadboard, DMM, and supplies. These materials will be used in ECE 2004/3004 and in ECE 2504/3504. Note that each degree program requires three of these four courses and many students take the fourth as an elective. The expected cost of all materials for students taking all four courses is $170 (about $42/course)." Eighty five percent (85%) of the students responded positively to the statement "Based on your experience in ECE 2004 and possibly in ECE 2504, do you believe that $42/course is a good value?"

Discussion and Conclusions:

Student responses to the six quantitative questions concerning the implementation of Lab-in-a-Box in our introductory circuits course clearly indicate that they believe the experiments enhanced their learning (74% agree or agree strongly), that the level of complexity of the experiments is about right (75%), that the number of experiments is about right (68%), and that Lab-in-a-Box should be continued in future courses (83% agree or agree strongly). This level of response is gratifying, although we have concern for the roughly 25% who, for one reason or another, appear not to have had a good experience. The students' perceived value of Lab-in-a-Box as it will be used in four courses supports our faculty view that the more sophisticated equipment we have selected and the more sophisticated and elegant experiments this equipment allows justify the increased expense over that which would be required for implementing the original University of Washington concept in a single circuits course.

There is a surprising consistency among the responses to the free-form question about the strengths of Lab-in-a-Box. The phrase “hands-on” is mentioned explicitly in 17 of 49 (35%) of the responses. Other phrases that appear often are “visualization,” “interesting,” and “fun.” These results are completely consistent with both the literature cited in the introduction as well as with the feedback we have received from focus groups of seniors in both degree programs. More importantly, these concepts were mentioned more forcefully by our senior female students in our focus groups. Thus, hopefully, Lab-in-a-Box will be helpful in attracting and/or retaining females and other under-represented minorities in our department.

Future work will involve developing experiments to accompany our recently-introduced second circuits course that is required of all EE students. These experiments will involve the introduction of transformers, the use of advanced circuit techniques such as Laplace and Fourier transforms, the introduction of circuit transfer functions, and the discussion of two-port systems. These more advanced techniques will require that students use PSpice to simulate circuits to assure that what they design is what they actually build. We expect that it will be possible to perform these advanced experiments by simply adding low-cost components to the course-specific bag of parts.

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Bibliography:

[1] NSF grant 03-43160. RWH is PI with six co-PIs from the ECE Department.

[2] Hendricks, R.W., and A.B. MacKenzie, manuscript in preparation (2005).

[3] McKeachie, W.J., P.R. Pintrich, Y-G Lin, D.A. Smith, and R. Sharma, Teaching and Learning in the College Classroom: A Review of the Research Literature (2E), Ann Arbor: University of Michigan (1990).

[4] Bransford, J.D., A.L. Brown, and R.R. Cocking, How People Learn: Brain, Mind, Experience, and School, Washington: National Academy Press (2000).

[5] Felder, R.N., and L.K. Smith, *Learning and Teaching Styles in Engineering*, J. Eng. Ed. **78**(7), (1988), pp 674–681. See also a recent update to this paper at http://www.ncsu.edu/felder-public/Papers/LS-1988.pdf.

[6] Felder, R.N., *Matters of Style*, ASEE Prism **6**(4), (Dec 1996), pp. 16-23. (http://www.ncsu.edu/felder/public/Papers/LS-Prism.pdf)

[7] Margolis, J., and A. Fisher, Unlocking the Clubhouse: Women in Computing, Cambridge: MIT Press (2003).

[8] Thom, M., Balancing the Equation: Where are Women and Girls in Science, Engineering, and Technology? New York: National Council for Research on Women (2001).

[9] Felder, R.N., and R. Brent, *Learning by Doing*, Chem. Eng. Ed. **37**(4), (2003), pp. 282–283. (http://www.ncsu.edu/felder-public/Columns/Active.pdf)

[10] Myers, C., and T.B. Jones, Promoting Active Learning: Strategies for the College Classroom, San Francisco: Jossey-Bass (1993).

[11] The Lab-in-a-Box concept and name originated with the ECE Department at the University of Washington.

[12] All Virginia Tech students are required to own a laptop PC with appropriate specifications.

[13] Electronix Express, 365 Blair Road, Avenel, NJ 07001. (http://www.elexp.com)

[14] Prof. R. Christie, private communication, (March 2004).

[15] Lai, K.M., J.B. Webb, and R.W. Hendricks, Lab-in-a-Box: Electric Circuits Experiments You Can Perform at Home, Version 2.2. (February 3, 2005). Available on request from RWH (robert.hendricks@vt.edu).

[16] Alexander, C.K., and M.N.O. Sadiku, Fundamentals of Electric Circuits (2E), New York: McGraw-Hill, (2003).

[17] Nilsson, J.W., and S. Riedel, Electric Circuits (6E), Englewood Cliffs: Prentice Hall, (2001).

[18] Tront, J.G., PSpice for Basic Circuit Analysis, New York: McGraw-Hill, (2004)

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