Teaching Linear Circuit Analysis Techniques with Computers

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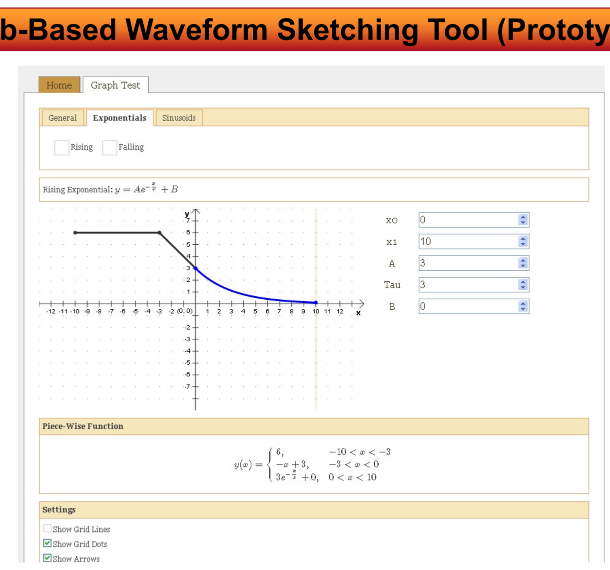
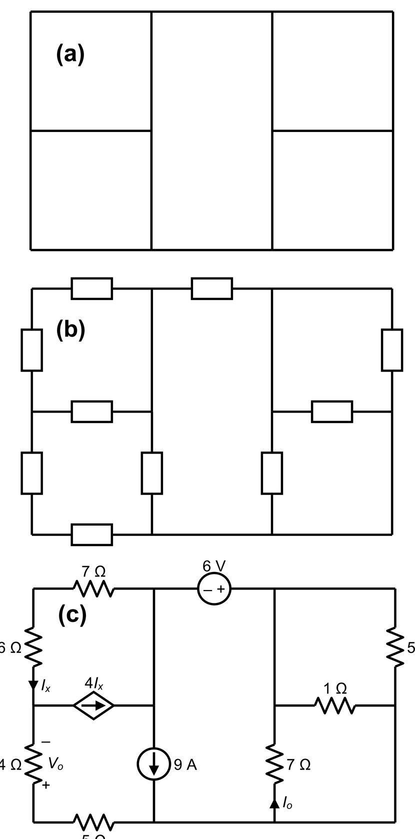
Motivation

- Analysis of linear circuits is a foundational topic in electrical engineering, and is also required for many other engineering majors, for whom it may be most or all of their exposure to electrical engineering
- Success rates are often low in these courses due to several factors, in our opinion:
  - Misconceptions about basic electricity coming into course, which may be frequently unrecognized by instructors[1]
  - Insufficient interactive activities
  - Delayed and/or inaccurate feedback on homework and assessments
  - Insufficient number and variety of worked examples are available to allow students to progress gradually up to the level of homework problems
- Our goal is to develop and rigorously assess novel software tools to improve student learning through practice in a highly interactive system capable of providing immediate, accurate, and highly relevant feedback regarding errors
- We are including special types of problems and targeted tutorial exercises to focus on developing qualitative understanding and on correcting typical student misconceptions
- The software is modular so it can be used in various ways, to generate automatically gradable homework sets and exams, interactive exercises for use during class, textbook problems & examples, and in a full tutorial system designed to supplement conventional instruction
- Students work for varying periods of time according to their needs, until they reach pre-defined levels of competency

Web-Based Waveform Sketching Tool (Prototype)



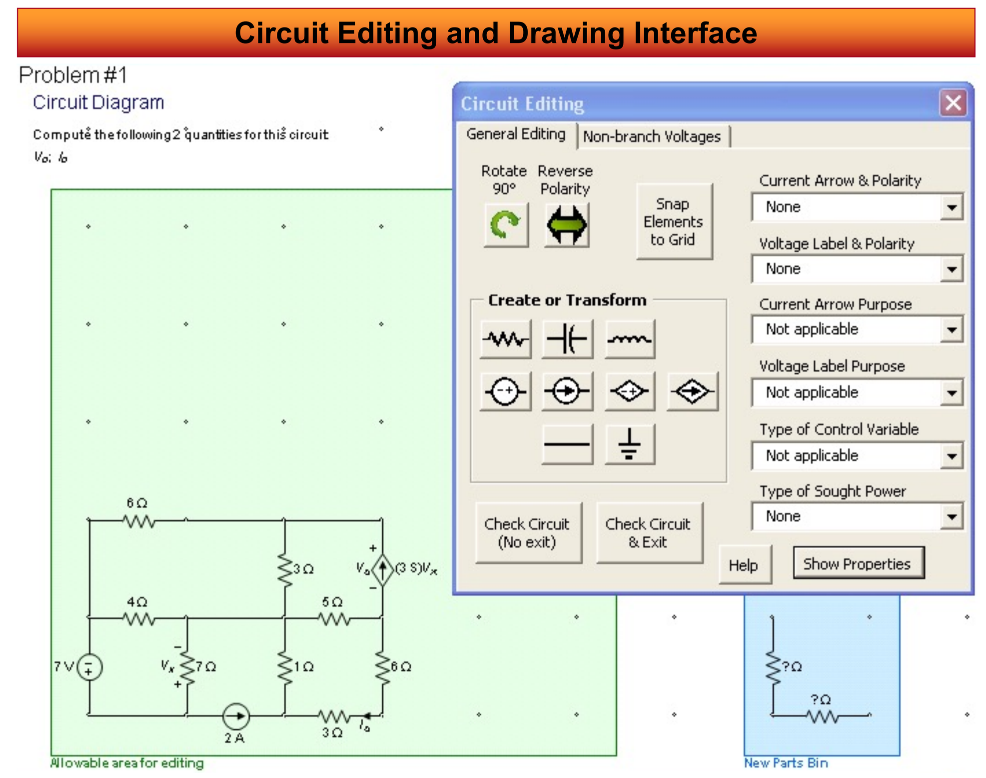
Three-step Process for Circuit Generation



Circuit Generation Procedure

- Circuits are generated as layouts, not netlists, since beginning students may not recognize the equivalence of circuits laid out differently, and specifying layouts guarantees planar circuits suitable for mesh analysis
- All circuits are laid out on a square grid of points for convenience; *any* planar circuit can be represented this way
- Randomly placing circuit elements on a grid and then checking them for validity is not a workable approach for anything other than very small circuits; the number of possibilities is vast and only a tiny fraction are valid
- We therefore use a three-step process for circuit generation, using special algorithms at each stage designed to maximize the probability of circuits being valid
- First step involves placing "shorts" and "opens" on the square grid; opens always stay open, but some of the shorts are later changed to circuit elements [Fig. 1(a)].
- Second step changes the required number of shorts into generic circuit elements, which are later changed to specific elements [Fig. 1(b)]
- Third & final step changes the generic elements into specific circuit elements, assigns values and polarities, control variables for dependent sources, and gains [Fig. 1(c)]

Circuit Editing and Drawing Interface



Effects on Student Learning

TABLE I. LEARNING GAINS IN LABORATORY STUDY

	Exptl. Group	Pre-Test Score	Post-Test Score	Gain
Average	Textbook*	58.6	61.6	2.9
Median	Textbook	60.5	67.0	1.5
Std. Dev.	Textbook	25.3	28.0	14.1
Average	Software**	57.8	86.4	28.6
Median	Software	57.0	85.0	30.0
Std. Dev.	Software	22.1	11.5	14.9
Std. Dev.	Pooled	23.0	20.5	14.1

*16 users. **17 users.

TABLE II. RESULTS OF LABORATORY-BASED COMPARISON, BROKEN DOWN BY TOPIC AREA

Topic	Exptl. Group	Pre-Test Avg.	Post-Test Avg.	Gain
Series/ Parallel	Textbook	72%	68%	-4%
Series/ Parallel	Software	71%	91%	20%
Node Equations	Textbook	49%	57%	8%
Node Equations	Software	49%	83%	34%

TABLE III. RESULTS OF INSTRUCTIONAL MATERIALS MOTIVATION SURVEY (SCALE = 1-5, 5=BEST)

Group	Statistic	Total	Attention	Relevance	Confidence	Satisfaction
Software Users	Means	3.54	3.44	3.22	3.94	3.62
	Std. Dev.	0.40	0.49	0.60	0.52	0.66
	Medians	3.57	3.54	3.11	3.83	3.75
Textbook Users	Means	3.01	2.84	2.99	3.51	2.65
	Std. Dev.	0.77	0.80	0.83	0.99	0.91
	Medians	3.01	2.88	3.00	3.72	2.33
Comparisons	Diff. of Means	0.53*	0.60*	0.23	0.44	0.97*
	Pooled Std. Dev.	0.58	0.64	0.70	0.75	0.76
	Cohen *d*-value	0.91*	0.94*	0.33	0.58	1.27*

*Statistically significant difference with $p < 0.05$.

Assessment of Student Learning

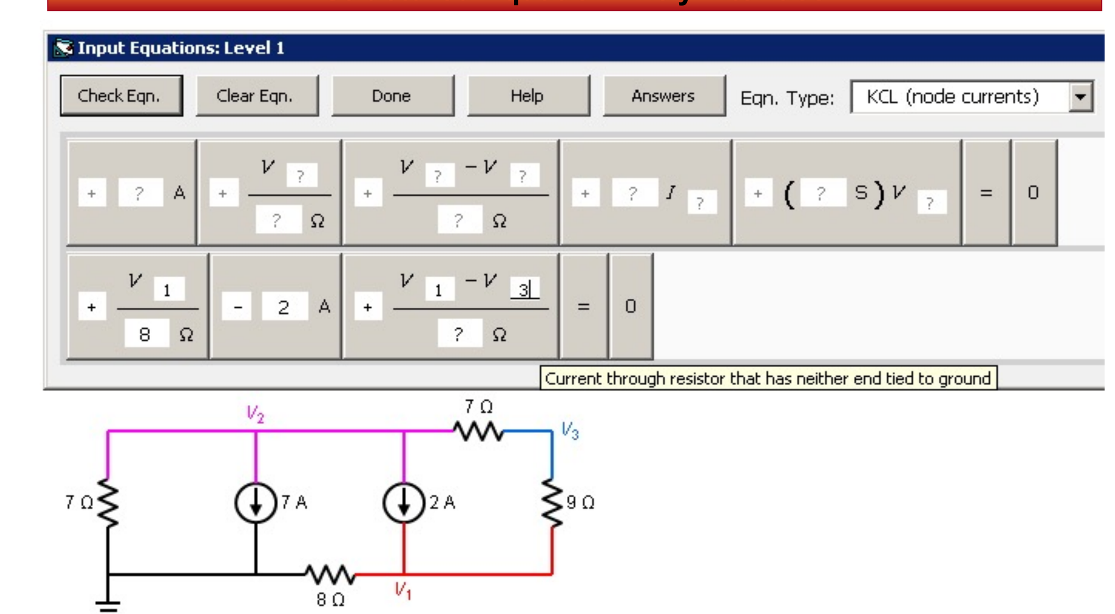
- A randomized, controlled laboratory-based study was conducted in Dec. 2012 using 33 paid student volunteers, all of whom were currently enrolled in EEE 202 or had completed it in the past year
- Students were given a pre-test and a post-test covering I) identification of series/parallel elements (qualitative topic) and II) writing node equations for a DC resistive circuit (quantitative topic), each lasting 25 minutes; two test forms A and B assigned randomly
- All students were given a copy of the textbook and instructed they could consult it as needed to review the topics
- Control group was assigned to work textbook problems related to topics I and II for 25 min. and 35 min., respectively; experimental group used software tutorials on these topics for the same times (probably insufficient to complete the tutorials)
- Results are shown in Tables I and II; the learning gain for software users was about **10X higher** than for textbook users. Difference was statistically significant, $t(19.7) = 3.303$, $p < 0.05$. I.e., textbook users improved only from a high "E" to a low "D," whereas software users improved from a high "E" to a solid "B"
- Students showed marked improvements on both topics (Table II), but a larger gain for the node equations (probably mainly due to lower pre-test scores in that case)
- On the simpler node analysis problem (current sources & resistors only), the average score on the post-test for software users was 98%, vs. 70% for textbook users (from pre-test scores of 59% and 57%, respectively)
- Effect size, defined as difference in post-test scores divided by pooled standard deviation of post-test scores (Cohen's *d*-value), is $d = 1.21$, which is considered very large
- The Instructional Materials Motivation Survey (IMMS) of Keller [3] was administered to both groups. The results in Table III show that the software motivates the students significantly better than the conventional textbook

Student Satisfaction with Tutorials

TABLE IV. RESULTS OF EMBEDDED SOFTWARE SATISFACTION SURVEY

Game Type	Date	very useful	somewhat useful	not very useful	a waste of time	very or somewhat useful
Series-Parallel	Summer 2012	56.3%	31.3%	6.3%	6.3%	87.5%
Node Equations	Summer 2012	50.0%	50.0%	0.0%	0.0%	100.0%
Series-Parallel	Fall 2012	60.7%	32.1%	7.1%	0.0%	92.9%
Node Equations	Fall 2012	61.5%	26.9%	7.7%	3.8%	88.5%
Mesh Equations	Fall 2012	61.9%	33.3%	4.8%	0.0%	95.2%
Series-Parallel	Spring 2013	70.2%	27.8%	1.0%	1.0%	98.0%
Node Equations	Spring 2013	79.8%	19.1%	0.0%	1.1%	98.9%
Mesh Equations	Spring 2013	82.4%	17.6%	0.0%	0.0%	100.0%

Structured Equation Entry Interface



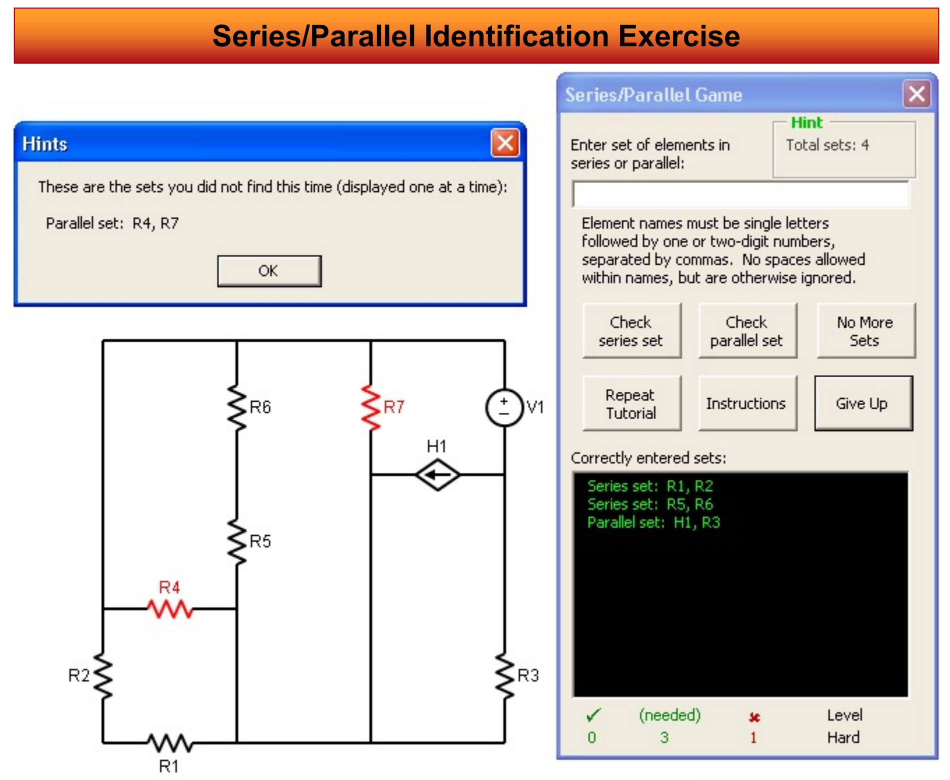
Software Modules Under Development

- **Problem Generation Module**
  - Generates unlimited supply of circuits similar to textbook problems and examples according to user specifications, randomly varying topology of circuit as well as element values
  - Currently produces DC circuits. Currently extending to AC steady state, transient (switched), and basic features of Laplace analysis
- **Solution Generation Module**
  - Goal is to generate fully worked solutions very similar to those found in solution manuals, but in a clearer, more consistent format and free of errors, without requiring human labor
  - Solution techniques will include voltage and current division, combination of elements in series and parallel, nodal and mesh analysis, superposition, source transformation, use of Thévenin & Norton equivalents, and combinations of the above methods.
- **Student Input & Validation Modules**
  - Program accepts a rich variety of inputs, including numerical inputs in tables, matrices & vectors, equations (in a special structured format), re-drawn (graphically edited) circuits (e.g., as steps in a solution), and (currently under development) waveform sketches generated using a graphical drawing interface
  - Above inputs are checked against computer-generated solutions, giving in-depth feedback to the student
- **Tutorial Interface Module**
  - Presents tutorial scripts to student, which make use of the other modules
  - Tracks performance and completion automatically to a central server
  - In the future, this data can be used to provide real-time feedback to instructor as to major points of difficulty being experienced by the class

Pedagogical Features

- Can color code nodes to help identify them
- Can color series & parallel sets red to highlight them
- Can color code currents leaving a node or supernode and voltage drops around a loop
- Structured equation entry interface (shown at far right) helps guide student learning

Series/Parallel Identification Exercise



Student Usage of Tutorials

- Over 365 students used three tutorials (identifying series and parallel elements, writing node equations, and writing mesh equations) in Summer 2012, Fall 2012, Spring 2013, and Summer 2013 in EEE 202 (Circuits I) at ASU and at two community colleges
- An embedded satisfaction survey was administered, asking students to rate how useful the software was in helping them learn the material (Table IV), and asking for open-ended comments (Table V)
- In the latest software version (Spring 2013), ~99% of respondents said it was very or somewhat useful, and 74% (overall) said it was very useful; results were somewhat higher for the equation writing than for the qualitative series-parallel module
- Student comments were generally very favorable (Table V)

Pedagogical Feature: Relating Terms in KCL Equation to Currents Leaving a Supernode

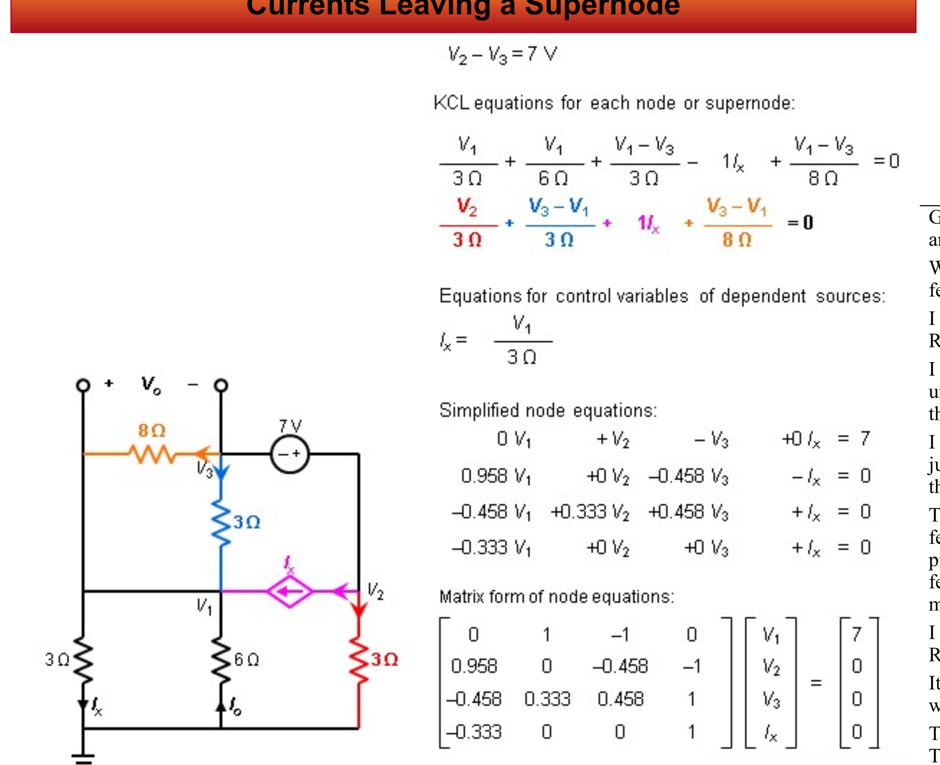


TABLE V. SAMPLE STUDENT COMMENTS ON TUTORIALS

Good job on the game! It was actually fun going through it and trying to do a good job! Thanks for making this.
Worked as intended, didn't take too long, kind of fun, and I feel like it helped!
I HAVEN'T EVEN LEARNED IT YET BUT IT WAS REALLY EASY TO GRASP USING THIS! YAY
I really thought it was awesome; it was very helpful. I understood the concepts, but this helped me develop a thought process on it.
I like how you are not marked off for getting on wrong, you just get to try again. You only really fail if you give up, and that is reassuring.
These modules honestly do help me learn circuit analysis. I feel that it is extremely helpful to have a good amount of practice problems, and a system that provides instant feedback. This helps me learn the correct techniques and master
I AM A PRO AT THIS. Major self-confidence booster. Really though, I feel like I'm talented at this node analysis!
It definitely helped me understand supernodes, I think this was more usefull than book work
This exercise helped me understand loop analysis very well. The assignment was great.
I would prefer to have a statistics page showing # of correct and incorrect attempts and possibly even a ladder [leader?] board showing how well different students did as opposed to everyone getting a congratulatory gold medal for doing thier hw
Wow is all i can say... This is the best, better than any hw I have done so far

Summary

- Our software modules generate random linear circuit problems similar to those in textbooks, as well as fully worked solutions following methods typically taught in introductory circuit analysis courses
- The system accepts student inputs in form of equations, numerical answers, matrices & vectors, re-drawn (graphically edited) circuits, and will also accept waveform sketches
- A controlled laboratory trial of two of our initial tutorials yielded a ~10X improvement in learning compared to textbook exercises, with a large, statistically significant effect size of $d = 1.21$
- Eventual goal is open-source distribution (e.g., through a MOOC) and/or commercialization via integration with textbook publisher web site that supports circuits textbooks (e.g., WileyPLUS)
- Additional partners and software users are always being sought!

References

[1] P. V. Engelhardt and R. J. Beichner, "Students' understanding of direct current resistive electrical circuits," Am. J. Phys. **72**, 98 (2004).

[2] A. Ioinovici, *Computer-Aided Analysis of Active Circuits* (Marcel Dekker, New York, 1990)

[3] J. M. Keller, *Motivational Design for Learning and Performance: The ARCS Model Approach*. New York: Springer, 2010.

Acknowledgements

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