Computer-Aided Instruction for Introductory Linear Circuit Analysis

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Motivation

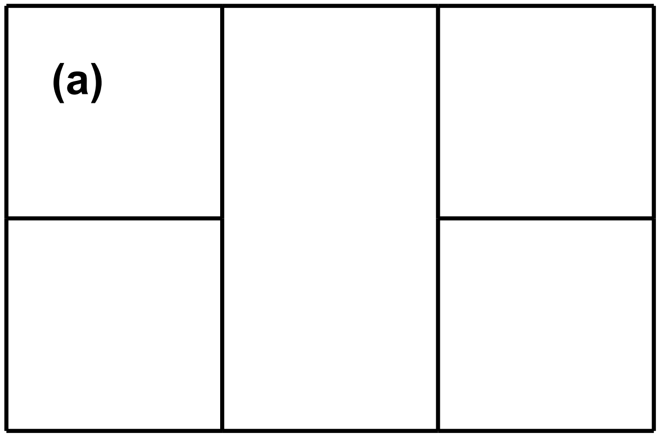
- Linear circuit analysis is foundational to electrical engineering, and is also studied by many other engineering majors (often as their sole introduction to EE)
- Students often struggle with the course for several reasons:
  - Inadequate examples available in textbook
  - Delayed and/or inadequate feedback on homework
  - Lack of active learning and interactive engagement
  - "One size fits all" approach to lecturing, inability to learn at own pace
  - Errors in textbooks and solutions, causing great frustration
- A possible approach is the user of computer aided instruction, as studied by various prior workers
  - While many were useful, most prior projects developed only incomplete or partial prototypes, or have not been rigorously evaluated to assess their effects on student learning
  - Publisher web sites typically offer algorithmic versions of the book problems, but usually involve only <u>answer-based</u> tutoring

Motivation (cont.)

- VanLehn found that such answer-based tutors typically yield an ave. effect size (Cohen *d*-value) of 0.31, whereas step-based tutors that accept each step of a student's work and give them feedback have an ave. effect size of 0.76 (compared to 0.79 for expert human tutors). [*Educat. Psychologist* **46**, 197 (2011)]
- We are therefore developing a step-based tutoring system for linear circuit analysis that accepts & evaluates a wide variety of student input, including equations, re-drawn circuit diagrams, simplified systems of equations, matrix equations, numerical answers, waveform sketches, multiple-choice answers, etc.
- A novel feature is that the system generates an unlimited supply of circuit problems & examples that differ in both topology and element values, as well as fully worked solutions (not just answers), using the same methods students are taught (unlike PSPICE)
- Various special pedagogical features are included to enhance learning, including an emphasis on conceptual topics

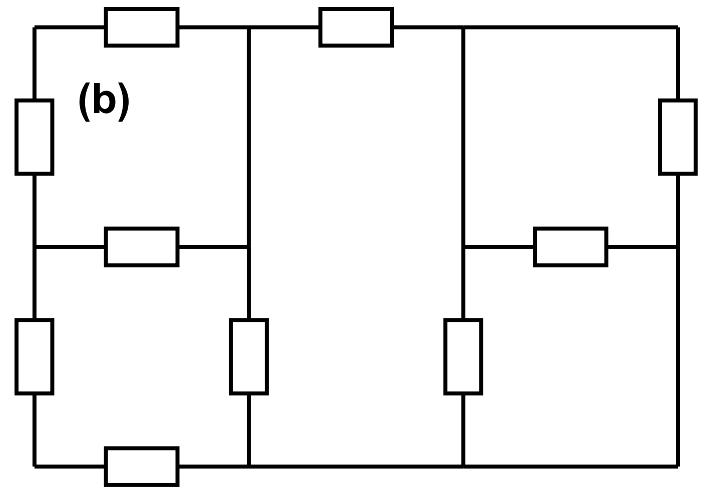
Circuit Generation Methodology

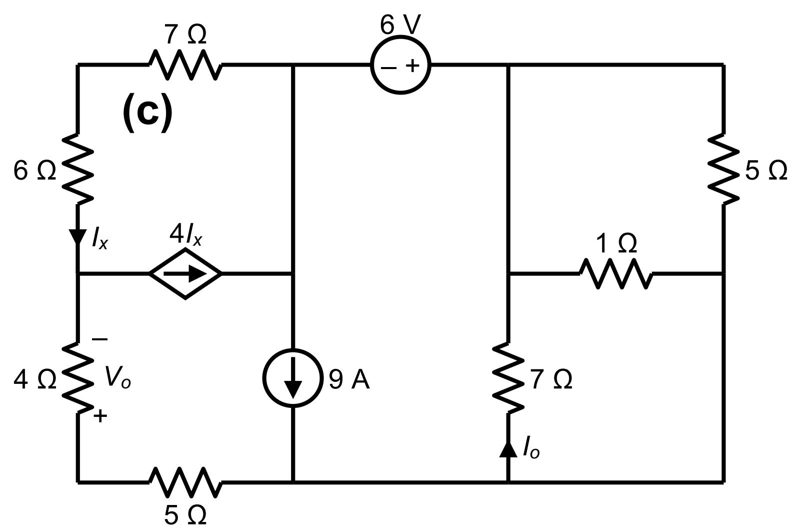
- We generate circuit layouts rather than netlists (helps ensure planarity for mesh analysis)
- Circuits are laid out on a square grid to make the graphical display easier (can represent *any* planar circuit this way)
- Randomly placing circuit elements on a grid and throwing away bad circuits is combinatorially infeasible for anything but very small circuits
- We therefore adopted a three-step approach, using special algorithms at each stage
- In the first step, we generate a “topology” consisting only of shorts and opens, where opens always stay opens, but some or all shorts later become circuit elements
- Topology determines number of meshes
- Must make sure it is not “hinged” (can be drawn such that two or more parts are connected by a single wire)
- Algorithms ensure it fills grid, is fully connected, and has no “dangling” shorts



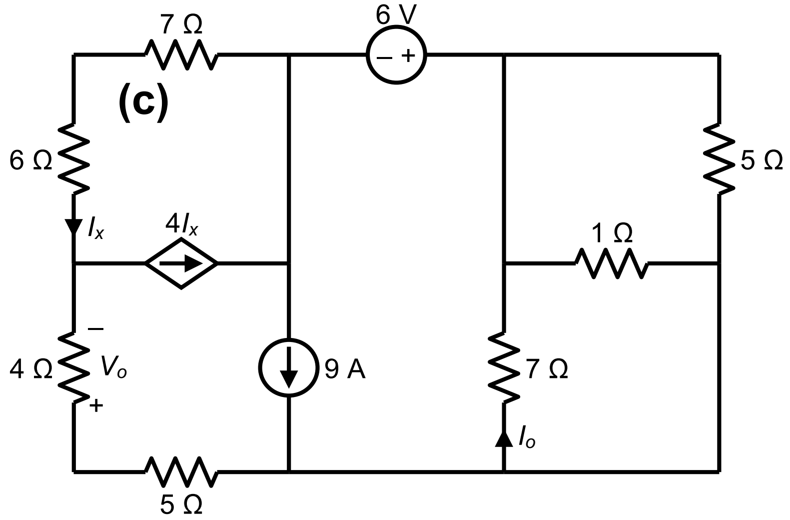
Circuit Generation Methodology (cont.)

- In the second step, the desired # of shorts are randomly changed to generic circuit elements, placing at least two elements per mesh (including outer mesh) to avoid shorted elements and meshes of shorts (which would reduce the true number of meshes)
- Must check again that it is not hinged after placing elements
- We then replace generic elements by actual ones of the desired type(s)
- To avoid insoluble problems, we find all or many trees of the network, randomly select one, and place voltage sources and inductors on twigs, and current sources and capacitors on links





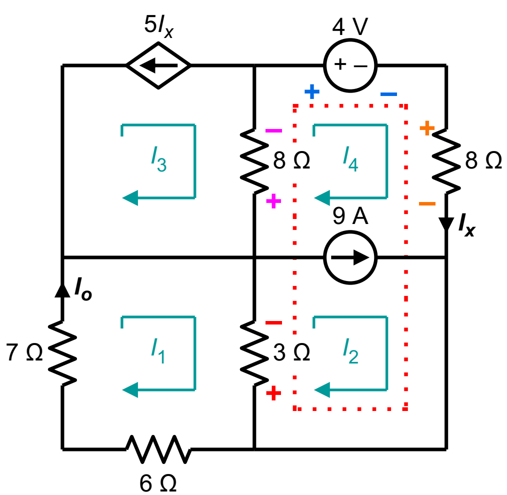
Circuit Generation Methodology (cont.)



- Above process ensures no loops of only voltage sources and inductors, or stars of only current sources and capacitors (in DC case)
- Can limit number of voltage sources in series & current sources in parallel
- Can optionally prohibit passive elements of same type in series and parallel with each other
- Can prohibit redundant sources and elements (such as voltage sources in series or parallel with current sources)
- Can specify # of floating supernodes and # of supermeshes
- Element values and control variables randomly assigned, following certain rules
- Circuit is checked and rejected if not soluble (can happen due to dependent sources)
- “Sought quantities” also selected randomly (currents, voltages, or powers)

Solution Generation

- Node or mesh equations are generated automatically, then simplified and cast in matrix form for solution
- Can optionally "pre-simplify" circuit by combining passive elements and sources in series or in parallel, showing re-drawn circuit at each stage
- Currently solves DC circuits by node & mesh analysis, but in process of extending it to use many other methods (voltage & current division, superposition, source transformations, Thévenin & Norton equivalents, etc.) and to handle AC, transient, and Laplace circuits as well



Current constraint equations:

$I_2 - I_4 = 9$ A

$I_3 = -5I_x$

KVL equations for each mesh or supermesh:

$I_1(7\ \Omega) + (I_1 - I_2)(3\ \Omega) + I_1(6\ \Omega) = 0$

$(I_2 - I_1)(3\ \Omega) + (I_4 - I_3)(8\ \Omega) + 4\ \text{V} + I_4(8\ \Omega) = 0$

Equations for control variables of dependent sources:

$I_x = I_4$

Solution:

$V_o = -21.3$ V; $I_o = 1.60$ A

$I_1 = 1.60$ A; $I_2 = 8.56$ A; $I_3 = 2.22$ A; $I_4 = -0.444$ A; $I_x = -0.444$ A

Simplified mesh equations:

$$\begin{aligned}
0\,I_1 &+ I_2 &+ 0\,I_3 &- I_4 &+ 0\,I_x &= 9\\
0\,I_1 &+ 0\,I_2 &+ I_3 &+ 0\,I_4 &+ 5\,I_x &= 0\\
16\,I_1 &- 3\,I_2 &+ 0\,I_3 &+ 0\,I_4 &+ 0\,I_x &= 0\\
-3\,I_1 &+ 3\,I_2 &- 8\,I_3 &+ 16\,I_4 &+ 0\,I_x &= -4\\
0\,I_1 &+ 0\,I_2 &+ 0\,I_3 &- I_4 &+ I_x &= 0
\end{aligned}$$

Matrix form of mesh equations:

$$\begin{array}{c}
\begin{array}{ccccc} I_1 & I_2 & I_3 & I_4 & I_x \end{array}\\
\begin{bmatrix} 0 & 1 & 0 & -1 & 0\\ 0 & 0 & 1 & 0 & 5\\ 16 & -3 & 0 & 0 & 0\\ -3 & 3 & -8 & 16 & 0\\ 0 & 0 & 0 & -1 & 1 \end{bmatrix}
\end{array}
\begin{bmatrix} I_1\\ I_2\\ I_3\\ I_4\\ I_x \end{bmatrix} = \begin{bmatrix} 9\\ 0\\ 0\\ -4\\ 0 \end{bmatrix}$$

User Input Modules

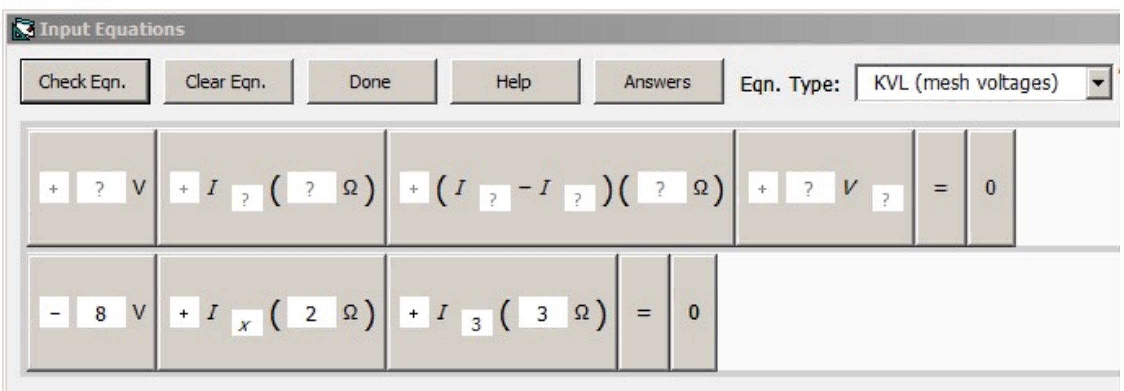
- Equations are inputted by the student using templates to guide them, where they select the appropriate term types and fill in the blanks
- Forms are used to input simplified sets of equations, and matrix equations
- Feedback is given immediately on correctness of their entries, to avoid wasting time solving incorrect equations
- Numerical answers for unknowns are entered on a form

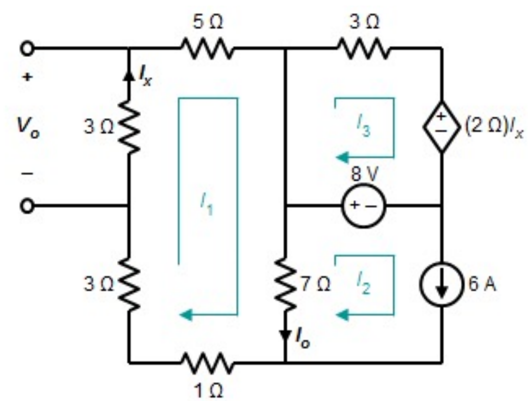
Problem #1

Circuit Diagram

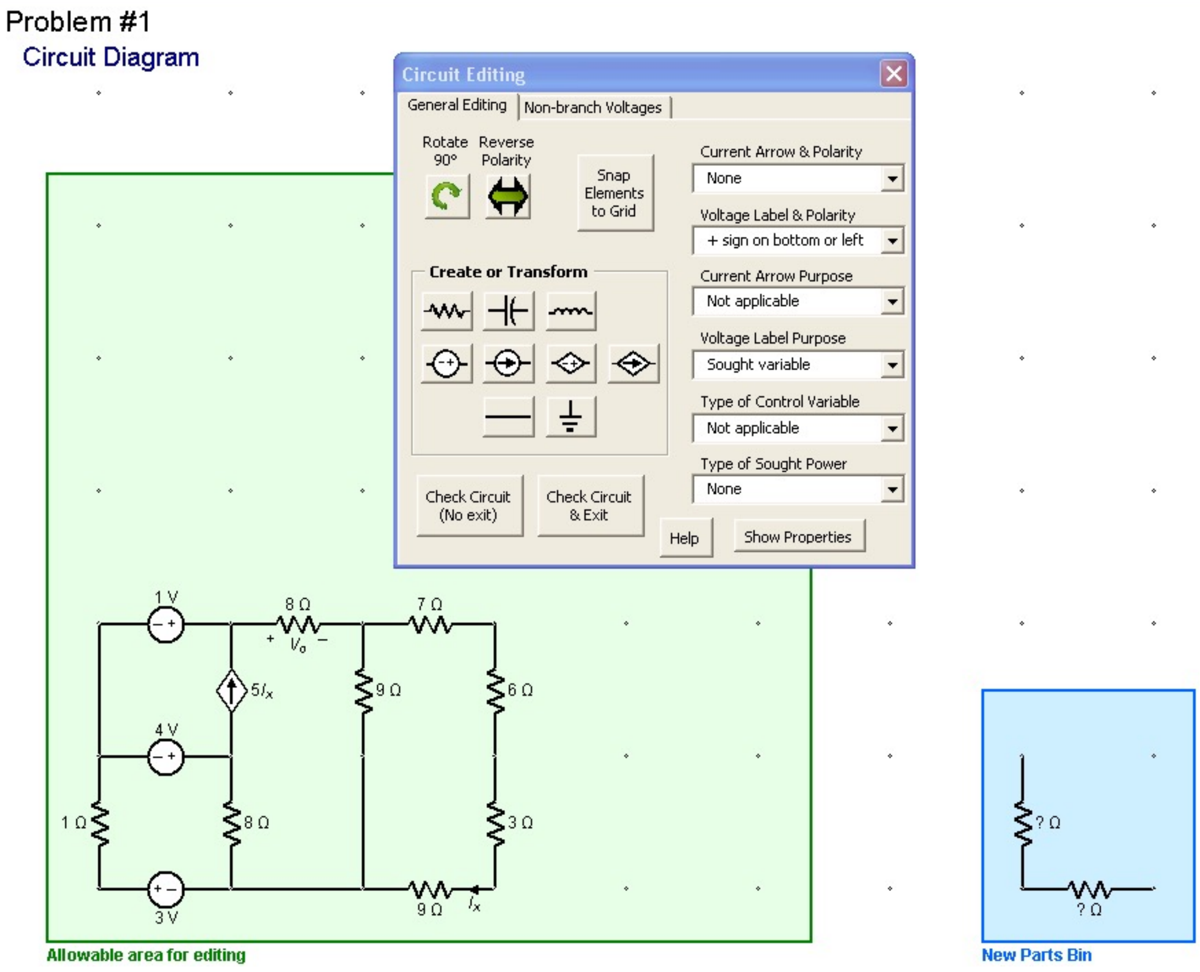
Compute the following 2 quantities for this circuit:

V_o; I_o



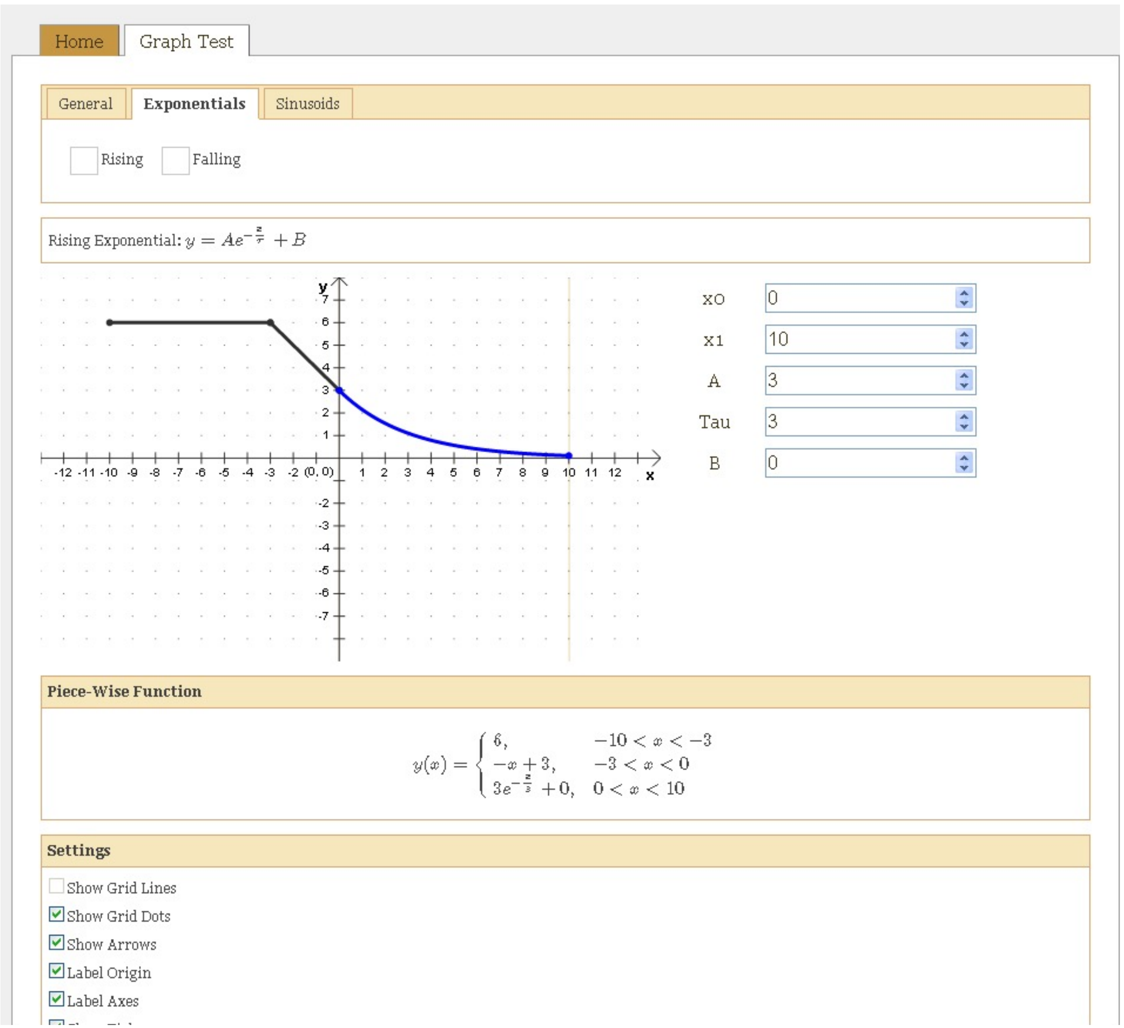


Circuit Drawing/Re-drawing Interface



- Currently implemented in PowerPoint (re-doing it as a form)
- Can change element values, move or transform them, add new ones, etc.
- Will be used in exercises where series/parallel elements to be combined, superposition, source transformation, etc.

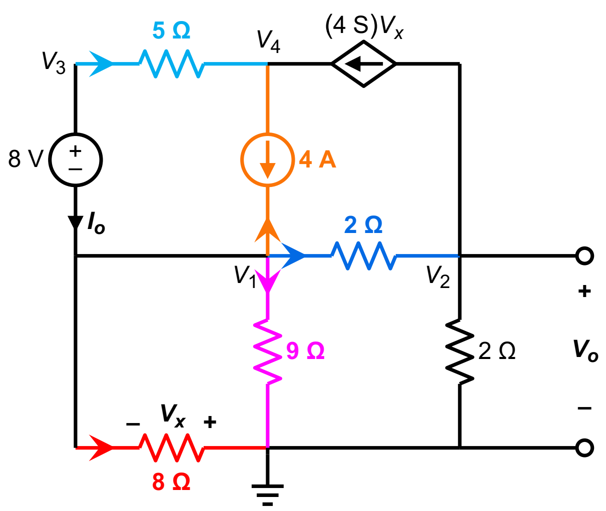
Waveform Sketching Interface



- Web-based system (currently prototype)
- User can sketch piece-wise functions graphically
- Can be used, e.g., for problems where student is given current through a capacitor and asked to find voltage, etc.

Pedagogical Features

- Can color-code nodes to help visualize them, or even erase elements to make nodes more obvious
- Can highlight currents leaving a node or supernode and color-code terms in corresponding KCL equation to show how the equation is formed
- Can highlight voltage drops around a mesh or supermesh and do similar color-coding for KVL equations
- Can highlight sets of series or parallel elements (or wye or delta sets) in red to emphasize them



Each colored arrow corresponds to a term in KCL equation #1 of 3.

Voltage constraint equations:

$V_3 - V_1 = 8\ \text{V}$

KCL equations for each node or supernode:

$$\frac{V_1}{8\ \Omega} + \frac{V_1}{9\ \Omega} - 4\ \text{A} + \frac{V_1 - V_2}{2\ \Omega} + \frac{V_3 - V_4}{5\ \Omega} = 0$$

$$\frac{V_2}{2\ \Omega} + \frac{V_2 - V_1}{2\ \Omega} + (4\ \text{S})V_x = 0$$

$$4\ \text{A} + \frac{V_4 - V_3}{5\ \Omega} - (4\ \text{S})V_x = 0$$

Equations for control variables of dependent sources:

$V_x = -V_1$

Tutorial Modules

- Developed three tutorials to date, covering identification of elements in series & parallel (conceptual), writing node equations, and writing mesh equations
- Students can view unlimited number of examples at various levels of difficulty, and then proceed to exercises at those levels
- Can give up and see answers at any time, supplemented with pedagogical features to clarify them
- Just get a new problem of same type & difficulty if they are unable to complete a given problem, with no penalty
- Emphasizes mastery learning; students must master skill to proceed
- Allows students to work at their own pace, with as much or as little practice as they need
- A tutorial authoring and execution engine are in development, to allow instructors to define their own sequences and include expository material as desired

Laboratory-Based Study

- Carried out randomized, controlled study using 33 paid student volunteers to compare effectiveness of our tutorials to traditional, textbook-based exercises (all students were taking or had taken the relevant course in the past year)
- Covered both conceptual (series/parallel identification) and quantitative (node equation writing) topics
- Used pre- and post-tests of two different forms, randomly assigned
- Students were randomly assigned to work traditional textbook problems on the topics for an hour, or to use the software for the same period of time
- The Instructional Materials Motivation Survey (IMMS) of Keller was used to assess effects of the different approaches on student motivation

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.

- Learning gain is ~10X higher for the software users
- Large gains observed for both qualitative and quantitative topics
- Software users reached post-test scores of 98% on the easier node analysis problem (vs. 70% for textbook users) after 35 minutes
- Overall effect size is d = 1.21 pooled standard deviations (very large); significant at 95% confidence level [$t(19.7) = 3.303$, $p < 0.05$]

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 $p < 0.05$.

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

Classroom Trials

- Materials used on voluntary basis in Summer 2012 and Fall 2012 in our course EEE 202 (Circuits I); insufficient data to make good comparisons
- Materials were used on a usually mandatory basis in Spring 2013 and Fall 2013 in 5 and 4 sections of the same course at ASU by over 340 and 206 students, respectively (9 sections, 546 students total)
- Impact on student learning is difficult to assess to date given many other uncontrolled variables and limited coverage of course topics
- Student reaction has been very favorable. When asked to rate the tutorials as "very useful," "somewhat useful," "not very useful," or "a waste of time," about 99% have rated them as "very useful" or "somewhat useful" (with about 74% saying "very useful")
- The DIRECT concept inventory on DC circuit concepts [Engelhardt & Beichner, *Am. J. Phys*. **72**, 98 (2004)] has been used as a pre- and post-test in these sections; results to be reported elsewhere

Typical Student Comments (verbatim)

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

Conclusions

- A step-based tutorial system is being developed for linear circuit analysis courses, capable of generating an unlimited supply of error-free problems and solutions
- A rich variety of student inputs is accepted, including re-drawn circuits, equations, matrix and simplified systems of equations, numerical and multiple choice answers, and waveform sketches
- A tutorial authoring interface and execution engine is in development
- Student learning gains were ~10X higher for software users compared to students working conventional textbook problems for the same time in a controlled, randomized laboratory-based study (effects size of d = 1.21 standard deviations, better than the average for step-based tutors of 0.76)
- Student satisfaction was very high in both laboratory and classroom-based settings
- Future work will include extension to a much wider range of the course material, conversion to a web-based platform, and evaluation at several other universities (University of Notre Dame, University of Virginia, and University of the Pacific, etc.)