**Session 1532**

# Visualizing Pedagogical Circuits

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***Abstract***

*Visualization techniques are integrated with a circuit simulator and applied to pedagogical circuits to communicate circuit behavior in an intuitive way. Several representations of voltage and current are used to convey behavioral aspects of circuit operation. The result is an interactive computer program—CktViz—intended to lower the cognitive barrier to comprehension of circuit operation by graphically representing voltage and current relationships. A small scale educational assessment has been performed using students taking an introductory circuits course as subjects. The results show that CktViz has a positive and significant effect on students' qualitative understanding of circuit behavior.*

## 1. Motivation

A major challenge in teaching circuit theory is that many of the students have no intuitive understanding of the behavior of electrical circuits. While they have actual, hands-on experience with, for example, the mechanical properties of materials, their experience with electricity is often limited to switching lights and other equipment on and off.

Traditional instruction in introductory circuit theory centers on circuit diagrams with a few defined electrical quantities (voltage and current) identified on the circuit. Even the simplest of circuits contains a wealth of information that goes unseen by the student. Only a few of the values in a circuit are ever calculated in class or homework. The focus of attention is directed to one element or value at a time. Information about other values is often neither shown or seen. The limited visibility of the circuit voltages and currents seems natural to the electrical engineer because instrumentation—voltmeters, ohmmeters, oscilloscopes—typically show only one value at a time.

Moreover, hand-calculated results describing the state of the system from quantitative analysis methods (i.e. finding voltages and currents from equations) are necessarily obtained away from the circuit. In this process, the circuit is abstracted to a set of equations and numbers. Although they contain the same relationships as the original circuit, the correspondence between the circuit and equations is obscure.

While these analysis skills are important, design, which is receiving greater emphasis in engineering education, requires a qualitative understanding of circuit behavior. The traditional teaching process conveys very little about the qualitative behavior of the circuit, or qualitative relations among the circuit values. Although the diagrams are visual, the solution process is well suited to the verbal and intuitive learning styles, and poorly suited for visual and physical learners. No wonder many students leave basic circuit theory courses with a poor grasp of fundamental concepts like voltage and current dividers and Thevenin equivalents. No wonder others leave, or never pursue, electrical engineering because they cannot get past the quantitative abstractions of circuit theory. The challenge is to devise a way to effectively communicate qualitative circuit behavior to visual and physical learners.

## 2. Prior Work

Introductory physics lectures commonly use physical examples to illustrate the behavior of physical principles for visual and physical learners. This is difficult to do for circuits, where the behavior of actual currents and voltages is made visible only with difficulty and far from the actual devices. Moreover, the number of circuit theory students is smaller, so the resources available for investing in physical demonstrations is less. However, electrical engineers are quite comfortable with computer simulation. Using the graphical capabilities of computers, the simulation results can perhaps be made visible in a way that communicates qualitative behavior effectively.

Any discussion of circuit simulation and circuit theory pedagogy must start with PSpice [1]. There are excellent reasons for teaching PSpice at some point in the electrical engineering curriculum, but instruction in PSpice in the first circuits course may teach more about PSpice than about the circuits. Moreover, PSpice results appear away from the circuit, so the relationship of the results to the circuit remains an abstraction.

Other pedagogical simulators have appeared in the literature. In earlier implementations [2,3,4], polarity is indicated graphically, while voltage or current appear numerically. In one [5], graphics indicate abnormal circuit conditions. Zoghi et al. [6] show voltage magnitude graphically as arrow length. Kirchoff's voltage law can be seen qualitatively at a glance. Doering [7] effectively uses graphics directly on the circuit itself to show voltage and current relationships. Node voltages are represented as the node height above the reference plane and the current magnitudes are shown as the width of the vertical stripe below the conducting path. A trend to increasing visualization of circuit values is apparent.

A key aspect of qualitative behavior is the response of a circuit to a change in a parameter. Most reported programs use dialog boxes to change circuit parameters.

The work in this paper takes visualization a step further, emphasizes interactivity, and uses animation to illustrate transients in addition to traditional time series graphs. In addition, an attempt is made to evaluate the effectiveness of this approach in teaching circuit theory.

## 3. Visualization

Visualization is the graphical representation of numerical data. While it is a powerful tool, it is also easily misused. Tufte [8,9] provides good basic guidance on effective visualization. It is important for the visual relationships to be similar to the real ones that exist in the objects being visualized.

Circuits are fundamentally networks, where a network consists of nodes connected by branches, not 3D or 2D objects. A good circuit visualization is therefore a form of network visualization, which is a specialized form of scientific visualization. Network visualization has been applied in the telephone industry [10] and in power systems [11].

The challenges of implementing visualization techniques in educational applications are twofold: 1) to display as much information as possible in a clear and intuitive fashion, and 2) to effectively show relationships between variables. Effective visualization of a pedagogical circuit must be able to show all current flows and voltage values in order to give a global view of the relationships between various circuit parameters and voltage and current information.

Circuit operation can most effectively be shown if these relationships appear directly on the circuit itself. Associating voltages and currents with the circuit diagram helps to convey information about the events associated with a particular location. Voltage and current relationships for circuit elements can be established if they are shown near each other, rather than separately.

In an introductory level circuits course, students learn different methods of circuit analysis. First, the student learns how to analyze DC steady state conditions, then transients, and finally AC steady state circuits. Just as variations of solution methods are used for each analysis method, variations of visualization methods are used.

### 3.1 DC Steady State

In DC steady state analysis, circuit parameters are linear and constant. The information that describes circuit behavior consists of the topology, the node voltages and the branch currents.

Circuit topology information is commonly shown in an orthogonal representation, where elements are laid out in parallel or at right angles. Element parameters are labeled with numerical values. Resistance symbols are varied in width according to the value of the resistance as shown in Figure 1.

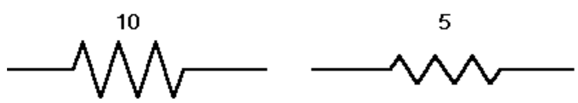



*Figure 1: Variation of resistance.*

Students regard resistors with high values as “large” and ones with low values as “small”. Varying resistor sizes according to their resistance values is thus an appropriate encoding for resistance.

Water pressure is a common physical analogy used for voltage. For DC circuits, water height, representing pressure, is used as a metaphor to create the encoding for node voltages, as shown in Figure 2. A box with an open top is placed on the circuit nodes. This represents a cup or water tank. The top of the cup is set at the maximum voltage in the circuit, and the bottom has a wider base to indicate that it is at the reference voltage (zero). As the voltage increases, the cup is filled with a blue bar chart, analogous to a cup being filled with water. Negative voltage levels drop below the reference line and are shaded gray.

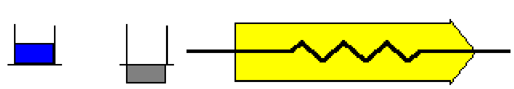


*Figure 2: Node voltage and branch current representation.*

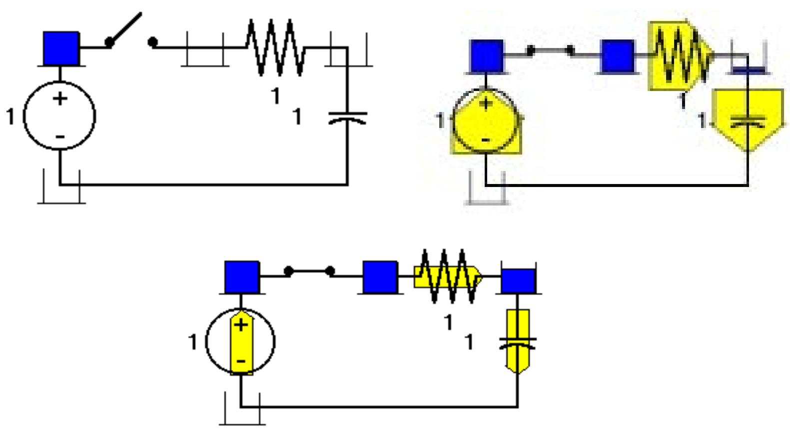
The physical analogy for current is water flow. As flow in a river, for example, increases, the river width increases. Thus the encoding of flow as width appears to be a useful natural encoding, as shown in Figure 2. For an introductory circuits course, this concept is an obvious choice for current flow. A distinctly different color (yellow) is used to distinguish current from voltages.

While the display primarily emphasizes visualization, branch and node numbers can be instantly seen by moving the cursor over the desired circuit element.

### 3.2 Switch Closure Transients

In transient analysis, circuit values vary with time. This variation must be communicated in the visualization. Changing circuit values can be shown in two ways: 1) animation, and 2) time series graphs. Both of these approaches are used in CktViz.

Through animation, voltage and current changes in the circuit can be seen as they happen. Seeing these changes communicates circuit behavior in a way that is different and not possible in time series graphs. Figures 3a, 3b and 3c are three frames from an animation of an RC circuit transient.



*3a)* *3b)* *3c)*

*Figures 3a, 3b, 3c: Animation of a switched RC circuit.*

Figure 4 shows the use of the more familiar time series graph. Each is placed at its value’s location in the circuit. These graphs have a double time scale so both short time constant and long time constant transients can be seen. The time series update is also animated, so changes in the circuit can be seen as they happen.

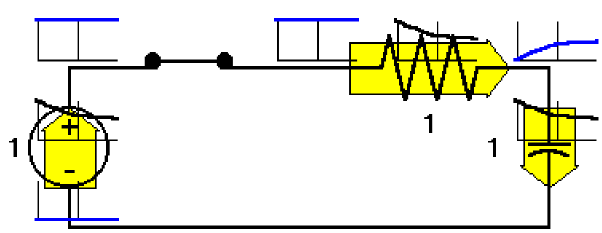


*Figure 4: Node voltages and branch currents represented by time series graphs.*

### 3.3 AC Steady State

Steady state AC circuit values are phasors with magnitudes and angles. Two different visualizations can be used. Figure 5 shows an encoding using height and width for voltage and current magnitude, respectively, and a pie chart for angles. Branch voltages, which are not as easy to determine from the node voltage visualizations as DC or transient branch voltages, are not shown in this encoding.

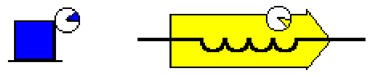


*Figure 5: AC node voltage and branch current representations.*

In the visualization in Figure 6 a conventional phasor diagram is drawn for node voltages at each node, and for branch currents and branch voltages at each branch. Current arrows are retained, as they seem to communicate magnitudes better than the phasors.

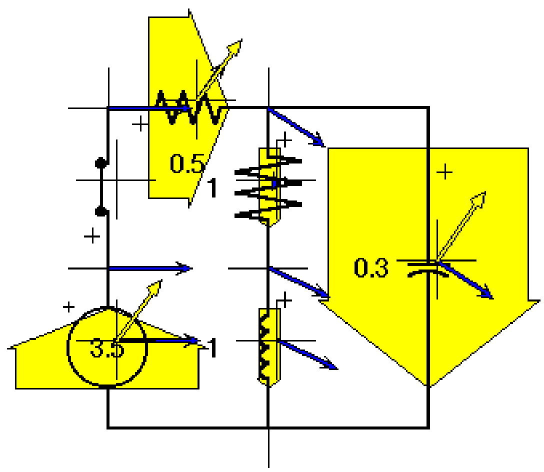



*Figure 6: Node voltage and branch current phasor representations.*

**4. Animation and Interaction**

Speed is a critical factor in designing a program to create graphical representations of pedagogical circuits for both interactivity and animation. The circuit solver routine was implemented in Visual C++ using modified nodal analysis. [12] The results from the circuit solver routine are used to generate the visualization of the circuit. Most of the execution time during a frame update is spent drawing rather than calculating. On a 100 MHz PC with unexceptional display hardware, frame rates of about 5 per second were achieved. While fast enough to make interactive updates seem instantaneous, animation is slow and jerky.

In the double buffered implementation it proved faster to redraw the old frame in the background color than to clear the internal buffer. While faster programming techniques could have been employed, the decision to use the available set of standard graphics routines represents a conscious trade-off between performance, programmer time and portability. No doubt hardware speed improvements will result in an acceptable frame rate.

Interactivity is achieved by dragging on circuit elements with the cursor. For example, placing the cursor at the center of the left resistor in Figure 1 and dragging up or down away from the center will increase its value. Each time the cursor position is read, the circuit is solved and the visualization updated. The result is a tight coupling between parameter changes and circuit behavior that provides a better feel for this relationship than making changes through a dialog box, although this is also provided for entry of exact values.

## 4. Assessment

To assess the effectiveness of CktViz, three small, short-term experiments were conducted with student volunteers from an introductory circuits course. In each experiment the volunteers were randomly divided into two groups, of about 10 students each. The experimental group received instruction with CktViz. The control group either received no visualization (experiments 1 and 2), or used PSpice in their instruction (experiment 3). The groups were surveyed and proved to have similar GPA and experience levels. The groups were taught on adjacent days at similar times and in similar conditions.

The students were taught one new concept for 30 minutes, given 30 minutes to complete several practice problems, and then given a 30 minute quiz that contained both qualitative and quantitative questions. Quiz scores for the qualitative and quantitative questions were the experiment results.

The subject of the first experiment was superposition in DC circuits. Average quiz results are shown in Table 1

*Table 1: Experiment 1 quiz average scores, percent correct.*

| Group | Qualitative | Quantitative |
|---|---|---|
| Control (non-Viz) | 45 | 40 |
| Experimental (Viz.) | 58.25 | 19.5 |

Students using the visualization program showed better qualitative understanding, but decreased quantitative skills. Students in the experimental group spent time learning how to use the program that the control group used to study the circuit theory subject. This training overhead has an exaggerated effect in a short term experiment.

The second experiment was modified to remove this effect. It was similar to the first except the students in both groups were given 30 minutes of training prior to the class portion of the experiment. Those in the experimental group received training on program usage. The control group was allowed to do homework assigned from class but not related to the experiment topic, which again was DC superposition.

*Table 2: Experiment 2 quiz average scores, percent correct.*

| Group | Qualitative | Quantitative |
|---|---|---|
| Control (non-Viz) | 42.5 | 20 |
| Experiment (Viz.) | 68.75 | 31.25 |

With training overhead removed, the results show that visualization had positive effect on both the qualitative and quantitative understanding of circuit behavior. The difference in the qualitative assessment is considered to be statistically significant.

The object of the third experiment was to compare visualization with PSpice. The subject was switched RC circuits with DC sources. Students in the control group were given training on, and instructed with PSpice. The results in Table 3 show that visualization had a positive effect on both the students' qualitative and quantitative understanding of circuit behavior, but the results are not statistically significant due to significantly lower attendance in one of the groups.

*Table 3: Experiment 3 quiz results.*

| Group | Qualitative | Quantitative |
|---|---|---|
| Control (PSpice) | 31.25 | 19.55 |
| Experiment (Viz.) | 37.5 | 23.7 |

## 5. Conclusion

The visualization concepts described in this paper effectively convey voltage and current relationships necessary for understanding circuit behavior. Results indicate that pedagogical circuit visualization does have a significant and positive effect on students' qualitative understanding of circuit behavior.

## 6. References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