Mechanistic Simulation in Electronics Engineering Education*

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Mechanistic simulation has been used to confer true user interactivity on a multimedia learning environment developed for World Wide Web access by electronics engineering students on and off campus. This paper demonstrates how the basic resources of lecture and tutorial material and laboratory notes have been supplemented with fundamental mechanistic simulations that enable students to gain understanding through self-paced experimental learning. Mechanistic simulation involves mathematical representation of a system in a manner that allows students virtual experimentation via control over adjustable parameters. Asymetrix ToolBook II has been used to construct four mechanistic simulations that explore key concepts within a second-year electronics subject. The topics covered are: BJT amplifier biasing circuit design, JFET amplifier load line analysis, and BJT amplifier midband gain performance and low frequency response analysis. The simulations also function as a dynamic resource for didactic lectures.

INTRODUCTION

THE MULTIMEDIA learning environment developed for electronics engineering students has been described previously [1]. Lecture material, laboratory notes and tutorial examples are included using both hypertext and graphical images. World-Wide-Web access has been made available to facilitate usage by both full-time and part-time students, both on and off campus.

However, placement of academic content into a multimedia environment does not, of itself, provide true interactivity. Although students can view the content of the learning environment at their own pace in whatever manner or sequence they desire, this amounts to little more than electronic page-turning if the information is presented in a more or less static or stereotyped form. This criticism holds even if the content is imaginatively garnished with dynamic multimedia effects unless the student can actually make a difference to what happens through interactive exploration of 'What if?' scenarios.

The use of mechanistic simulations answers this criticism. Mechanistic simulation involves mathematical representation of a system in a manner that provides students with control over adjustable parameters [2–4]. By testing the effects of variation in the values of adjustable parameters, students are able to learn through self-directed experimentation using 'virtual apparatus' that simulates the system being studied.

MECHANISTIC SIMULATION

Mechanistic simulations can be of two types, descriptive or fundamental. Descriptive simulations simply mimic the behaviour of real systems through the use of empirically chosen mathematical expressions while not necessarily purporting to represent their true mechanisms. Fundamental simulations use unique mathematical equations that are the inescapable expression of the nature of the proposed mechanism of a system; such simulations also necessarily mimic system behaviour.

This paper describes fundamental simulations based on the known mathematical relationships governing the behaviour of BJT amplifier biasing circuits [5], JFET amplifier load lines [6] and BJT amplifier midband gain performance and low frequency response characteristics [7].

TOOLBOOK IMPLEMENTATION

We have used Asymetrix *ToolBoook II Instructor* as the authoring tool for creating the simulations. This authoring tool provides a rich variety of objects, particularly draw objects, the properties of which can be dynamically manipulated at run time under programmed control. The programming language used was ToolBook's *OpenScript*. The ready availability of scriptable draw objects permits the creation of quantitatively precise simulations and animations with very low development costs. The most significant single cost-saving feature is the ability to produce dynamic animations without requiring the employment of graphic

artists to create animation cartoons. We have achieved a highly cost-effective development/delivery ratio of less than 10 person-hours of development per hour of delivery.

Concise descriptions will now be given of the four simulations developed. More detailed information may be found in the relevant papers in the bibliography.

BJT amplifier midband gain performance

This simulation allows study of the operation of a typical BJT amplifier circuit at the midband range of frequencies using the hybrid π transistor model. It is based on a detailed worked example presented in lectures and shows the effect of variations in each of the external circuit resistor values on two types of voltage gains calculated for this amplifier, i.e., $\mathbf{Av}_S = v_o/v_s$ and $\mathbf{Av} = v_o/v_i$.

In Fig. 1, the upper diagram shows the amplifier circuit schematic while the lower diagram depicts the corresponding midband small signal equivalent circuit. The results of various voltage gain calculations are shown underneath this.

To illustrate graphically the effect each resistor has on the voltage gains, the graphs on the right hand side show how specific voltage waveform amplitudes (v_s, v_i and v_o) vary as resistor values vary. Different colour waveforms denote specific combinations of resistor values recorded in the legend in a colour matching the respective waveforms. Students therefore get immediate feedback, both visually and numerically, of how the value of each resistor affects the amplifier's operation.

The user-operable elements of the user interface shown in Fig. 1 comprise the six variable resistors in the upper circuit diagram and the five control buttons. The amplitudes of the sine waves marked v_i and v_o are calculated directly from the numerical values for the variable resistors chosen by the user according to the laws governing the input-output relationship of the circuit. Both the numerical output and the calibrated amplitudes of the respective sine waves are scaled in relation to the amplitude of the source voltage v_s represented at the top right of the screen.

At all times when the wiper of a variable resistor is being dragged, the currently appropriate signals of v_i and v_o are displayed as dashed sine waves with amplitudes updated dynamically during the drag procedure as long as the left mouse button is depressed. Data are stored in the graph and legend.

A feature of all the simulations described here is that additional pop-up information can be displayed by *right*-clicking various parts of the interface (e.g., the equivalent circuit or the numerical output fields shown in Fig. 1).

More information regarding the operation of this simulation is contained in reference [7].

BJT amplifier low frequency response analysis

The second simulation allows study of the low frequency response of a typical BJT amplifier
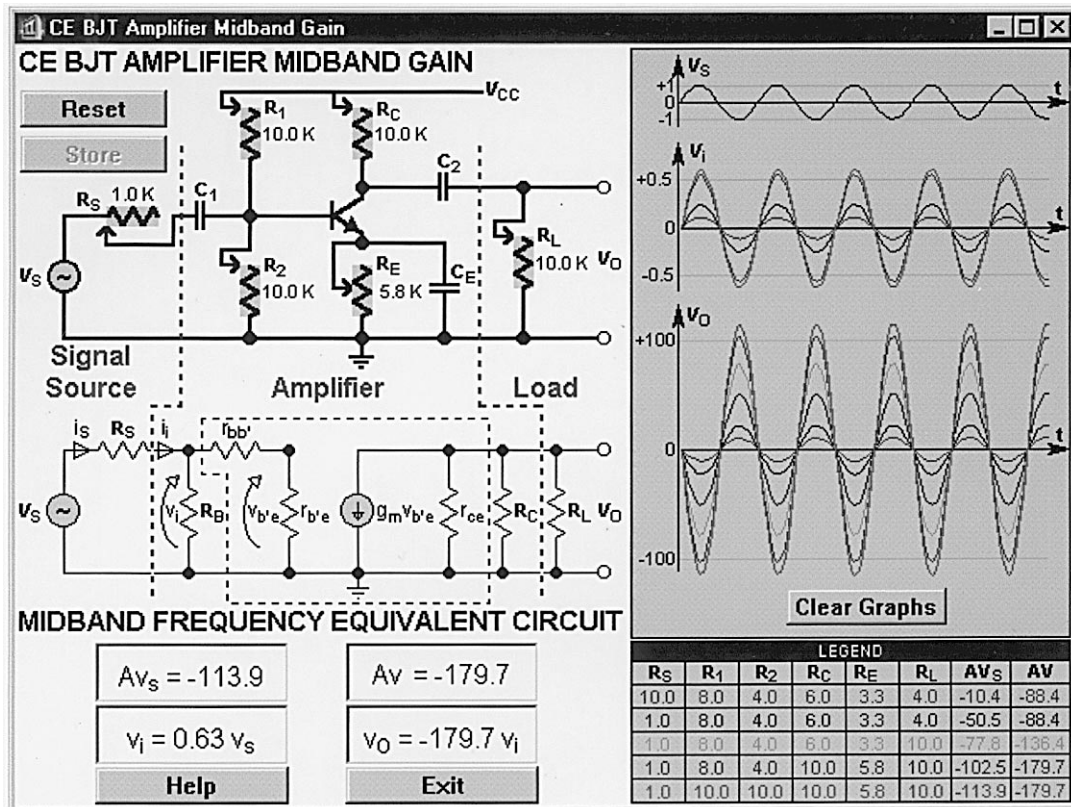

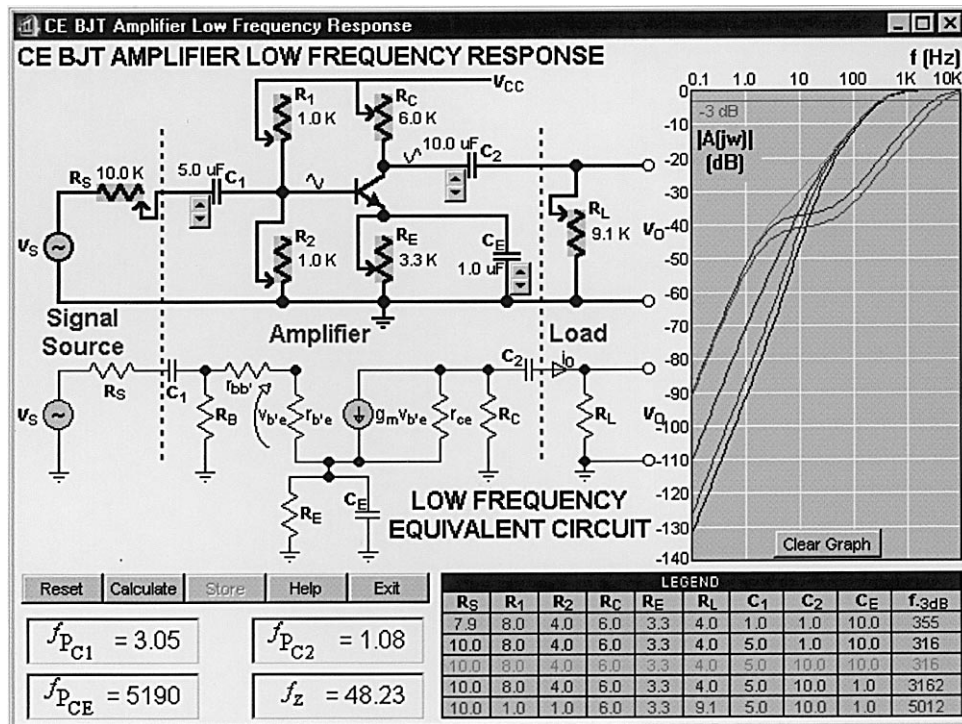Fig. 1. User interface for mid-band gain of BJT transistor amplifier.

Fig. 2. User interface for low frequency response of BJT transistor amplifier.

circuit using the hybrid π transistor model and is also based on a detailed worked example presented in lectures. It simulates the effect of variations in each of the external circuit component values on the location of pole and zero frequencies of the low frequency voltage transfer function.

In Fig. 2, the upper diagram shows the amplifier circuit schematic while the lower diagram depicts the corresponding low frequency small signal equivalent circuit. The calculated pole and zero frequencies are shown directly underneath this.

To illustrate graphically the effect each external component has on the low frequency response, the graph on the right hand side displays the amplifier's Bode magnitude (dB) plot for low frequencies up to midband for specific combinations of external components. Different colour waveforms denote specific combinations of external component values recorded in the legend in a colour matching the respective waveform. As in the first simulation, students get immediate feedback, both visually and numerically, of how each of the external components affects the amplifier's low frequency response.

The Calculate button calculates and displays as a dashed curve the low frequency response corresponding to the current values of the variable resistors and capacitors. This result may then be stored as a coloured solid line with a corresponding row of data in the legend. This calculation is made according to the laws governing the input-output relationship of the circuit, using the numerical values for the variable resistors and capacitors chosen by the user. More information

regarding the operation of this simulation is contained in reference [7].

BJT amplifier biasing circuit design

The third simulation allows students to perform the following tasks:

(a) design an operating bias point for two different single stage transistor amplifiers;
(b) study the temperature-dependent behaviour of both amplifiers in terms of bias point stability and, thereby,
(c) decide which of the two different amplifiers best meets the design requirements of a DC condition that is largely independent of transistor parameters and temperature.

In Fig. 3, the graphical displays of output characteristics with the load lines and Q points move dynamically and independently for the respective circuits in response to user-controlled variation of resistance values and temperature. The temperature panel contains a slider control for varying the temperature between $0°C$ and $125°C$, and displays the temperature-dependent variables I_{CB0}, V_{BE} and β (the ratio of I_C to I_B).

It is also possible to display graphs of I_C and V_{CE} versus temperature over a domain of $0°C$ to $125°C$ for each circuit under the conditions defined by the current choice of variable resistance values. The resulting plots for the default resistance values are shown in Fig. 4. The respective curves are colour coded for self biasing (red) and fixed biasing (blue), corresponding to similar coding for the headings of the respective circuit panels and the respective Q points and load lines.
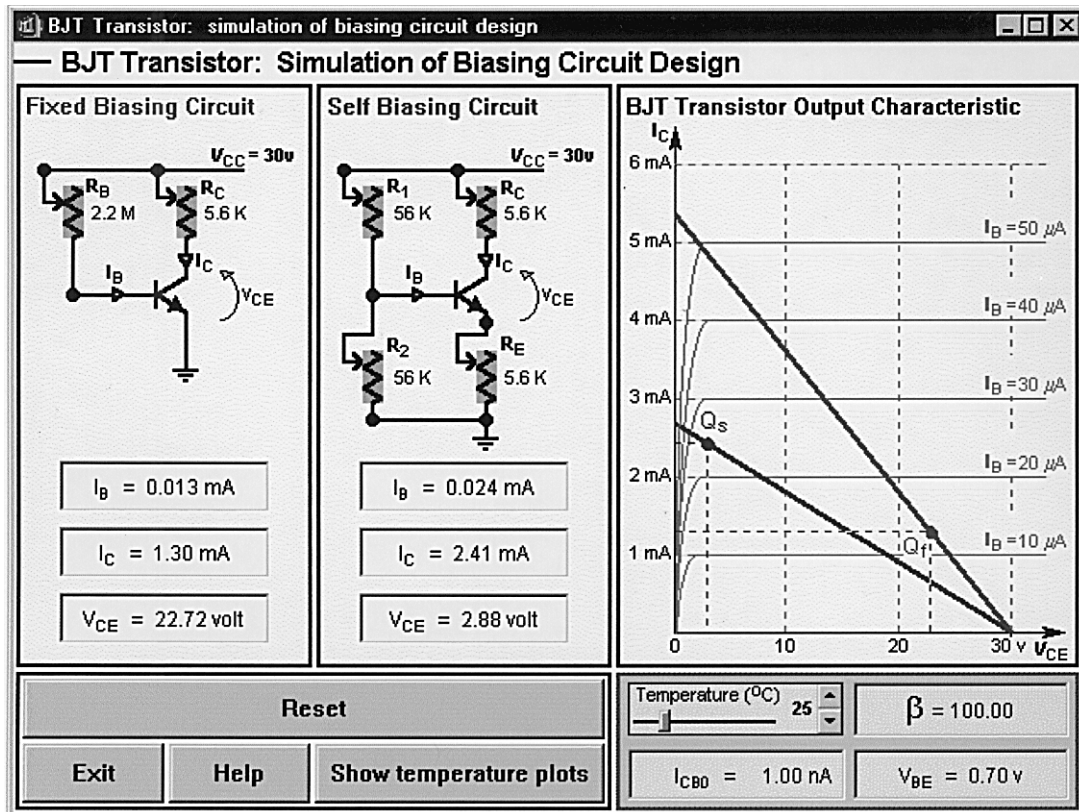
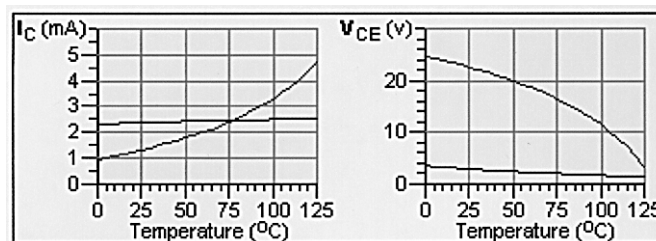Fig. 3. User interface for experimental study of biasing circuit design.

Fig. 4. Temperature dependence of I_C and V_{CE}.

The aim of the experiment is to choose resistor values for each circuit to achieve a given desired Q point and then to investigate the temperature stability of this Q point for both circuits.

Unlike the linearly variable resistors used in the first two simulations, the variable resistors for the biasing circuit simulation are logarithmic and stepped following the E12 resistor series. Variation of any of the adjustable resistors produces dynamically updated changes in numerical and graphical output.

The graphical output shows the load lines and Q points for the respective biasing circuits overlaid on a single BJT transistor output characteristic. The load line and/or Q point for a given circuit are redrawn dynamically during any 'drag' operation performed by the user on the wiper of any of the circuit's variable resistors. The corresponding numerical output fields are updated simultaneously.

When the temperature is varied by the user the transistor output characteristic is redrawn along with the Q points for both circuits, and the corresponding numerical output fields are updated. More information on this simulation is contained in reference [5].

JFET amplifier load line analysis

The fourth simulation allows students to perform the following tasks:

(a) design the correct operating bias point of a JFET amplifier;
(b) study the effects of this bias point on the amplifier AC and DC load lines;
(c) monitor the shape and phase relationship of the input and output waveforms at the bias point;
(d) study the amplifier voltage transfer characteristic of the amplifier for the AC load line, and
(e) notice how the amplifier voltage gain changes with changes in the bias point.
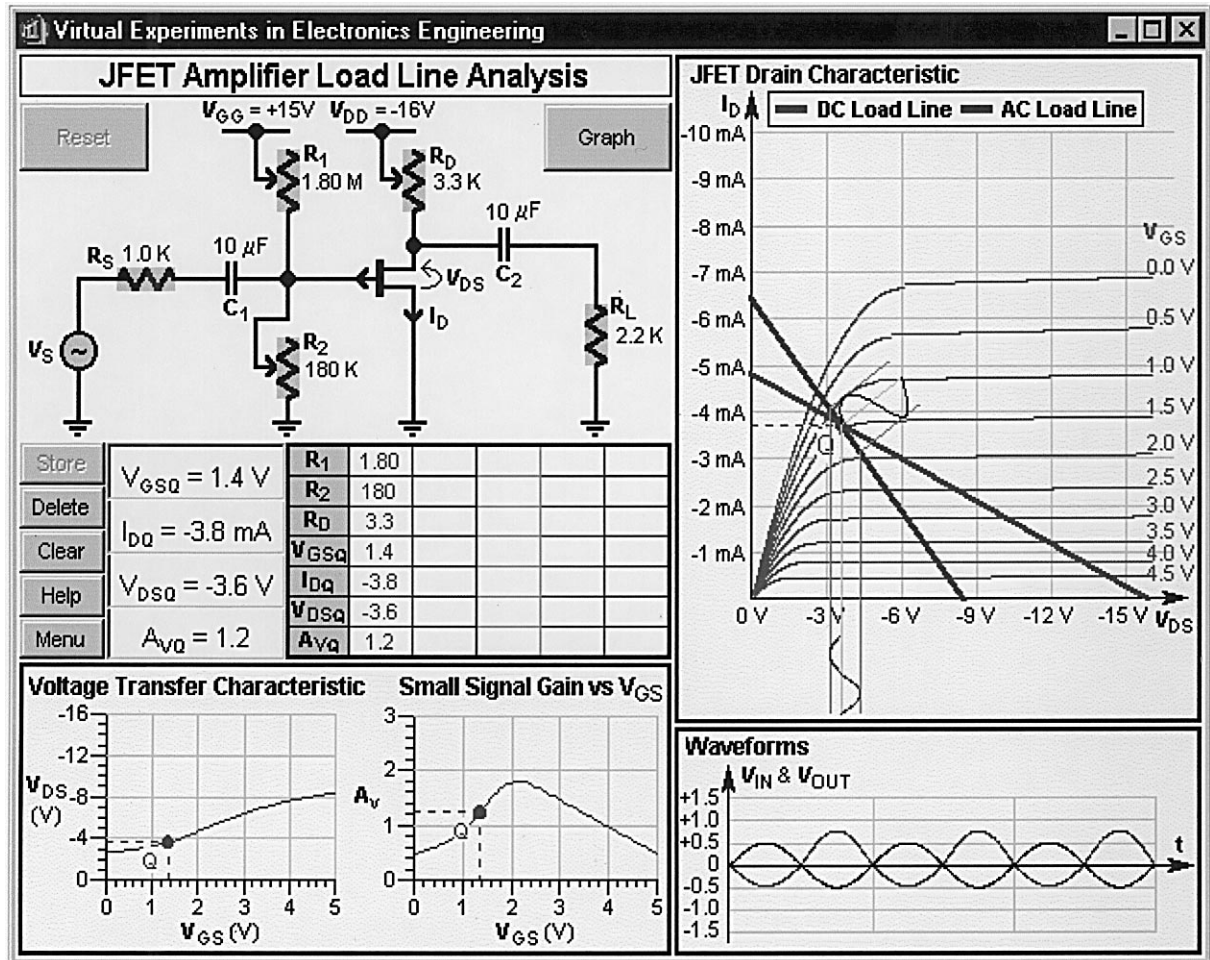
Fig. 5. User interface for virtual experimental study of JFET amplifier load line analysis.

This simulation was based on lecture notes and a laboratory experiment.

The user interface shown in Fig. 5 contains panels displaying the active circuit, the JFET drain characteristics, the voltage transfer characteristics and the current and stored input and output voltage waveforms.

The calculations for this simulation require solution of two algebraic equations, one of which is nonlinear. To achieve this, we constructed a Windows dynamic link library (DLL) based on the algorithm for Newton's iterative method contained with the Simulation Control Program (SCoP). The DLL was built and compiled using the SCoP DLL builder created with ToolBook by Hugh Kelly [8]. All the remaining calculations were made using ToolBook's *OpenScript* language.

METHODS OF DELIVERY

Lecture and tutorial demonstrations

All four simulations have now been utilised within lectures or tutorials as an aid to explaining difficult concepts in electronics engineering over the course of the last three years. In most cases, the students are presented with the theoretical background to a given electronics concept. A detailed worked example is normally provided next so as to reinforce the theoretical material.

Finally, a demonstration is given to the students of the simulation software with a view to:

- highlight specific 'difficult to understand' concepts;
- clarify the dynamic behaviour of the circuit under consideration;
- get the students using the simulations for their own self-paced study of a given problem.

Interactive assignment/laboratories

In addition to lecture/tutorial demonstrations, the simulations have also been used as a basis for class assignments and/or preparing students for specific laboratory experiments.

For example, the first simulation was used as a basis for a class assignment in 1996. All students were given a copy of the first simulation software, either directly from nominated student accessible computers or by downloading from a Monash University WWW site. Assignment questions were designed to lead students to understand:

- how the maximum values of **Av** and **Av**$_S$ were achieved;
- the difference between **Av** and **Av**$_S$;
- how the various external resistors affected the amplifier voltage gains;
- the important interplay between the three components of the amplifier system, i.e., the signal source, the amplifier and the load.

With respect to student laboratory preparation, the third simulation was based on an experiment performed manually by the students during the semester. By giving students access to this simulation before they actually performed the experiment, it was noted during the laboratory session that students appeared to have a much better grasp of the topic than had been experienced in previous years. Students were also able to appreciate the power of simulations in describing electronic circuit behaviour; using the simulation software they were able to complete in a few minutes what took them two hours to perform manually in the laboratory. Moreover, certain aspects of the educational design, which could not be implemented in the laboratory for practical and cost reasons, were easily incorporated into the simulation (e.g., extended temperature variation of the bias circuit operation).

CONCLUSION

The simulation and animation methods used in the applications described in this paper demonstrate highly cost-effective approaches to providing electronics engineering students with interactive resources for self-paced learning through the use of virtual experimental apparatus.

Student feedback has been favourable; many have found the simulation software very beneficial and have requested more such simulations to support this kind of learning. Typical comments obtained from students have included:

- *'The program that simulated a BJT amplifier was an excellent learning tool.'*
- *'We would like to see more of QED software which can be modeled for any transistor.'*
- *'To improve the WWW software, it would be useful to have lots more tutorials which show graphically any change in circuit parameters. This was done for DC biasing, but would be especially useful for showing changes in frequency response when resistors and capacitors have their value changed.'* (obtained prior to development of the second simulation)

These simulations of virtual experiments have been found to be useful for both on-campus or off-campus teaching and learning, and are readily distributable on diskette, on CD-ROM or via networks.

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Phillip Tran is currently a fourth-year medical undergraduate at Monash University. His participation in a first-year medical option on electronic authoring at Monash University's QED Research Unit (now privatised as QED Interactive Pty Ltd) led to his being invited to work on CBL developments with the QED team for the past three summers. His creative interest in computer programming has led to his co-authorship of several software titles, including Monash University's Engineering Mechanics CD-ROM and QED Interactive's Virtual Experiments in Electronics Engineering CD-ROM.