Enhancing Students' Systems Thinking: Four-Screen Representation of Electronic Systems

Iouri Belski
RMIT University, Melbourne, Australia
iouri.belski@rmit.edu.au

D. Campbell Gray
RMIT University, Melbourne, Australia
cgray@rmit.edu.au

Abstract*: Students of electronic circuit design often overlook important aspects of linear circuit performance. Their knowledge of the effects of steady-state and transient responses needs improved unification. A standard four-screen system representation is given for improving student learning. This representation consists of algebraic transfer function H(s), the pole-zero plot, the Bode plots of magnitude and phase, and a graph of the time response to a unit step. Questionnaire responses and test performances over the last six years confirm the effectiveness of the four screens in improving student learning. Further analysis of questionnaire responses leads to strategies for shoring up weaknesses in working with the less-understood screens. It also leads to software for implementing the four screens, making both large and small details accessible to graphic input and display, so as to form an improved tool for design and learning.*

Introduction

Engineers simplify systems by using models. Despite incomplete details, engineering models can usually represent systems with sufficient accuracy to provide designers with good evaluations of real situations. System models can usually be represented in various ways: mathematical, graphical, behavioural, etc. Each representation provides only a part of the whole picture. The representations characterise the system from different aspects and often complement each other, enhancing our understanding of the real system. The more representations we grasp, the deeper our understanding of the system.

Engineering education is based on modules and models. Academics often teach important laws, rules and models as separate modules, expecting students to build a 'big picture' and to comprehend interrelationships between various models and modules themselves (Nilsson (1983). This is similar to asking a viewer to analyse activity in a busy street from views of it through different windows, without providing help in establishing relationships between the views. Whatever is nearest, clearest, brightest and facing a viewer's window becomes the centre of attention. Distant, blurred aspects gain less attention. But they may contain the most important information or evidence.

Similarly, teaching of circuits and systems provides students with different views and does so over years. Algebraic transfer functions, pole-zero plots, and graphs of steady-state frequency response and of transient response represent different views which students receive. These views look very different and tend to be presented separately. Thus students tend not to relate them in their minds and they often lack the skills necessary to convert from one view to another. However, views which they miss in this way may contain the most important information.

A four-screen representation is adopted here, which allows a student simultaneously to view system behaviour through four different windows (Belski and Gray (2003)). Students are expected to view all four screens together, and establish a unified picture. They are asked, while looking at one screen, to develop the other three in their minds. This ensures enriched understanding of both the representations and the relationships between them. This is confirmed by student feedback and it should find successful application in other aspects of engineering education.

Basis for the Four Screen Representation

Designing an amplifier

Seven years ago the first author took charge of the third year degree course Electronic Engineering 3. This focuses on properties of real electronic circuits. It builds on the principles of ideal operational amplifiers and ideal feedback and prepares students to face problems associated with non-ideal properties of electronic components. While learning the influence of feedback on circuit behaviour following Sedra and Smith (1998) in 1999, students were given this design exercise:

(a) Design an amplifier with a voltage DC gain of 2 V/V±10%. The output voltage must not exceed 2.5V. The input voltage can reach a level of 1 V (DC). (b) Can an operational amplifier with the transfer function $H(s) = 208/(s^2 + 6s + 5)$ be used in your design?

For part (a), students proposed utilising a general non-inverting amplifier configuration (Figure 1) and choosing feedback resistors to be equal ($R_1 = R_F$) and of appropriate tolerance (5% or better).

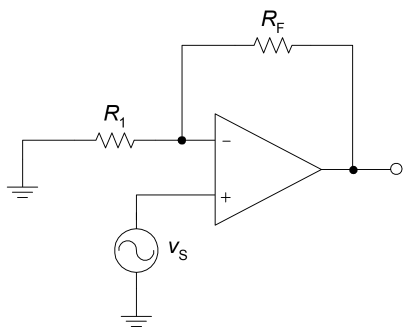

Figure 1: Amplifier design proposed by students

Students gave the amplifier gain as $A_f = 1 + (R_F / R_1) = 2$

With $A_f = 2$ V/V, they concluded that part (a) had been solved, because the maximum output voltage of $V_{out} = 2$ V fits the requirements. They also confidently declared that their design would also satisfy part (b), reasoning that 2.5 volts cannot appear at the output even when the gain is at the maximum permissible level of $A_f = 2.2$ V/V. They considered other details of the operational amplifier transfer function unimportant, because the main DC voltage gain requirement had been met.

However, students were reminded that the formula for A_f was correct only for infinite operational amplifier gain whereas the DC gain A_o of this operational amplifier is finite.

They said "Oops!" and substituted the formula $A_f = A_o/(1 + fA_o)$, where is a feedback factor.

Students this time calculated the closed-loop gain to be $A_f = 1.9$ V/V, cheerfully declaring their original proposal to be still valid, because it met the 10% gain range requirements. Some suggested a possible need for resistors to have smaller tolerance than 5%, say of 1%. Some students even proposed increasing the ratio of R_F to R_1 to 1.11 to reduce the DC gain of the closed-loop system to $A_f = 2$ V/V. However, most of the class decided to stay with the original proposal.

The students' approach looked well-founded, however their proposal was wrong. The DC gain of the amplifier will indeed be 1.9 V/V after it settles to a steady state following switching on. However, it needs to be switched on first to settle and the output will vary before settling.

Students ran PSpice simulations for both steady-state frequency response and transient response following switch-on, using schematics of Figure 2, and discovered problems.

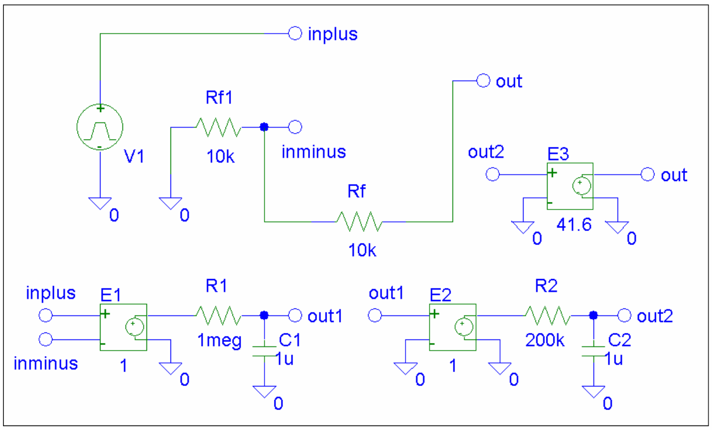

Figure 2: Closed-loop amplifier model used in PSpice simulation

Figure 3a shows that the closed-loop amplifier gain exceeds 6.85dB (2.2 V/V) around 0.3 Hz and even breaches the gain ceiling of 2.5 V/V (7.96dB) around 1 Hz .

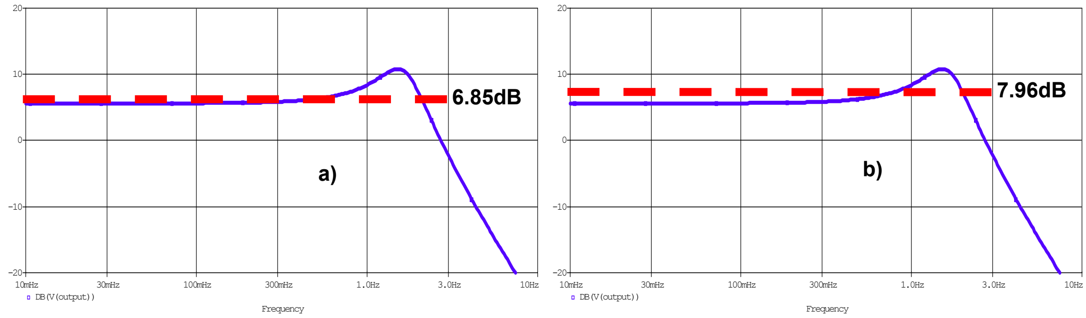

Figure 3: Magnitude of the closed-loop amplifier

Students had not expected these breaches and began to question their design. They saw that the main requirement for DC gain (6.85 dB maximum) had been met and some felt that this must keep the maximum output level below 2.5 V. They were reminded that amplification of the DC signal was the main concern. None perceived that the magnitude-response peak just above 1 Hz could render the design unsuitable.

With that point established, students were asked to perform a PSpice simulation of the transient response to a unit step arising from switching on. Figure 4 evoked great surprise, as the output exceeded the 2.5 V limit for more than 0.1 second, so the design was invalid.

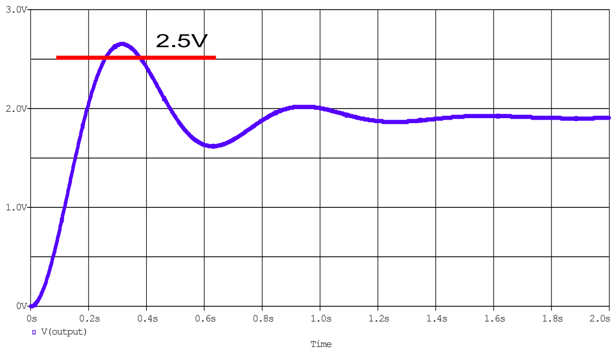

Figure 4: Transient response of the closed-loop amplifier

Design failure through lack of systems thinking

Students reacted to the transient response simulation with disbelief. Upon reflection they realised they had been preoccupied with the DC gain. As soon as this fitted the design requirements, they had assumed the rest of the characteristics of the closed-loop circuit must automatically follow. They neglected consideration of whether frequency response or transient response could provide them with useful additional information on the circuit's behaviour. The students simply did not recognise that the room they were in contained more windows which could help identify something important about the street. They needed to look through the other windows.

When the PSpice simulation results of both Figures 3 and 4 were revealed, students were gradually able to explain the reason for the inconsistency in their design. "The original operational amplifier", they said, "is overdamped, so it must not contain any magnitude peaks in its magnitude Bode plot. Also, it slowly reaches its level in transient response, without overshoot. Due to the feedback network of two resistors, the closed-loop amplifier of Figure 1 becomes underdamped. With the new pair of complex poles, the magnitude response experiences a peak and the transient response becomes a damped oscillation, overshooting the final settlement level. Therefore, the circuit might be 'in trouble' and can exceed the maximum output voltage threshold at the time it is switched on even though the DC gain is implemented to fit within specifications".

The students agreed that they already knew of the movement of poles due to the connected feedback. Nonetheless, as they were unaware of the interrelationship of all the circuit characteristics, they were preoccupied with the DC gain of the closed-loop amplifier, entirely disregarding its frequency and transient behaviour. They also were not ready to interpret the magnitude Bode plot (already obtained) and to relate the frequency behaviour of the circuit with its time behaviour in one combined picture. Time response and frequency response were not related in their minds to DC gain. Neither were they linked with one another. This was a clear indication that different models and different behaviours of a circuit need to be somehow presented to students as connected – as a part of one whole.

Developing a systemic picture

To assist students in developing better comprehension of electronic systems and to help them grasp circuit behaviour systemically, the authors have developed the four-screen approach to electronic system representation exemplified in Figure 5 (Belski and Gray (2003)).

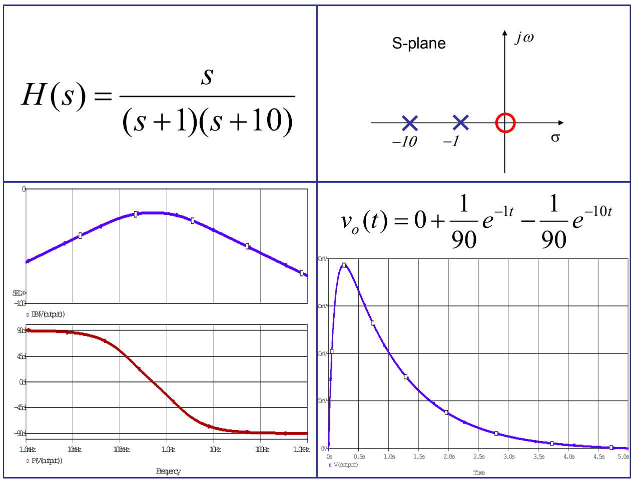

Figure 5: Four-Screen Representation of an Electronic System

Students are asked to ***always visualise all the four screens together*** before making any judgements on the circuit. This helps not only in a better understanding of the circuit's behaviour, but also ensures that their circuit design will not have obvious errors. The Four Screen Representation depicted in Figure 5 contains the following four screens:

Screen One: Transfer Function

Screen one (top left in Figure 5) holds the algebraic description of the system – its transfer function (TF). This description is general, and is sufficient for a professional to judge the whole range of circuit's behaviours. Nonetheless, being in general a complex function of a complex variable, it presents mathematical difficulties for students with insufficient skills in mathematics. Students of Electronic Engineering 3 only deal with transfer functions of first and second order.

Screen Two: Pole-Zero Plot

Screen two (top right in Figure 5) depicts the pole-zero plot (PZ) of the system. PZ is in a sense a graphical portrayal of circuit's poles and zeros. PZ helps in analysing system stability and issues such as suitability for further improvements by incorporating a feedback loop. It also provides graphic links between circuit diagrams and values on one hand and features of response in both time and frequency domains on the other.

Screen Three: Magnitude and Phase Bode Plots

Screen three (bottom left in Figure 5) contains Bode plots (BP) of magnitude and phase versus frequency on a logarithmic scale for steady-state sinusoidal inputs. Students can use both real and asymptotic Bode plots – whichever are easier to obtain.

Screen Four: Transient (Step) Response

Screen four (bottom right in Figure 5) reveals the response of a circuit to a unit step input. Students are asked to ascertain an algebraic representation of the output signal and to visualise its behaviour graphically. Proper evaluation of a circuit design nearly always requires acceptable transient response since the circuit will work only after the power supply is switched on.

The mental image of the four screens and their interrelationships helps in comprehending the whole. Often a designer is required to design an electronic system with the appropriate amplitude and phase response (Screen Three). Linking this back to Screen Two, the pole-zero plot, and then Screen One, the transfer function, establishes the relationships between the circuit and its break frequencies. In Screen Two, complex poles or zeros which are close to the $j\omega$-axis indicate resonant peaks or dips in the frequency response, away from the asymptotes, and sharp changes in phase around resonance. For poles, they also indicate the presence of "ringing" in transient responses and possible instability in some feedback situations. Pole positions may also indicate sluggish time response or overshoot, again pointing to Screen Four, and exposing potentially important issues which might otherwise have been overlooked. Once all four screens and their links are visualised, design processes becomes more complete and reliable.

Four Screens of the amplifier

It is certain that if students were exposed to the four-screen representation and have been able to visualise all the four screens for the amplifier in Figure 1, they would be in a much better position to foresee the problem of the overshoot and would implement appropriate design without guidance of academics. They were asked to deliver suitable DC gain, so they would be thinking of the appropriate appearance of the magnitude Bode plot (Screen 3). The Four-Screen approach would require them to think of the TF, the PZ and the transient response of the circuit. This would result in a deeper circuit analysis and in the four-screen representation of the circuit proposed by the students (Figure 1) is depicted in Figure 6 (Sedra and Smith (1998)).

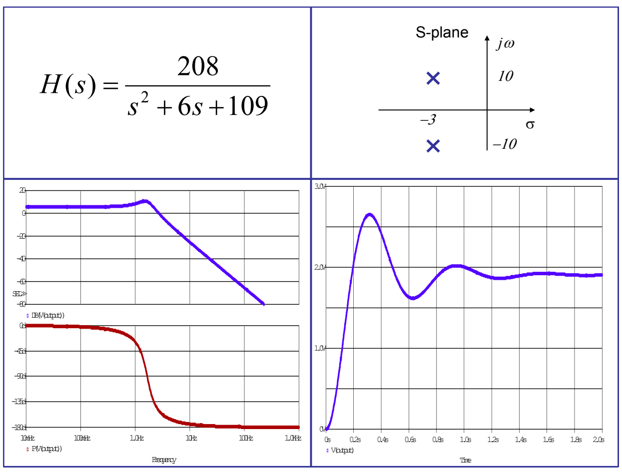

Figure 6: Four-Screen representation of the closed-loop amplifier

Certainly, anyone able to develop and visualise the four screens presented in Figure 6 could see that the design originally proposed by the students is faulty.

Evaluation

Student Performance

Teaching of the Four-Screen representation commenced in 2000 and has since been refined and given more emphasis. Before 2000, the representations were taught more separately. Relationships between the representations received less attention and when students were tested on them, they often performed poorly.

A progressive improvement occurred in students' final examination scores for questions related to the Four-Screen representation. Since 1999 the final examination has had a question requiring reconstruction of circuit behaviour from Screen 2 alone.

A 2006 examination question gave a pole-zero plot with poles at $-400 \pm j1000$ and a DC magnitude of 80 dB. Students were required to express transfer function $H(s)$ in algebraic form, find the damping ratio, estimate the peak amplitude overshoot and resonant peak magnitude. They were also required to draw Bode plots of magnitude and phase and scaled plots of the step response. Average student scores for this and similar questions since 1999 are shown in Figure 7.

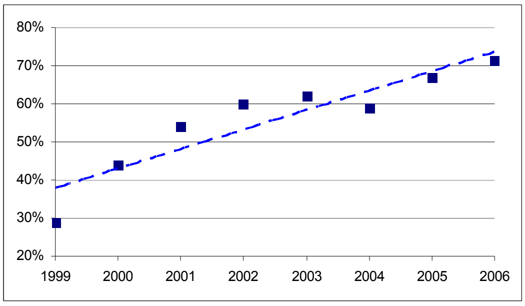

Figure 7: Average scores on reconstruction the circuit's behaviour from Screen 2 alone (final examinations 1999 to 2006)

The trend is very pleasing. The largest improvement occurred in 2000 – the first year of the Four-Screen approach. This is well identified by the logarithmic trend line in Figure 7. The data point of 1999 is well below the trend line. The rest of the data points are close to the trend line and identify gradual improvement. The observed improvement is partly attributable to strengthening of students' expectations that this topic would be examined. A growing body of tutorial exercises and past examination questions has also sharpened skills.

Student opinions on Four-Screen Representation

Two separate sets of surveys from 2004 to 2007 have provided data for this paper. Formal University Course Experience Surveys were conducted in week 10 or week 11 of the 13-week semester by an officer independent to the course, with 193 responses. Surveys by the authors were completed by 237 students in week 12 or week 13. Extracts from written responses in both surveys follow:

"It allows us to see the system as a whole". "... can see the relationship between the transfer function and Bode plots, Pole-Zero diagram..." "It helps to link things together and see the outcome of changing circuit parameters". "Enables a comprehensive overview of circuit behaviour. Draws together previous knowledge to allow better overall understanding and makes application of theory easier." "The ability to realise the circuit behaviour from only four screens (without much mathematics)". "The fact that information in one screen can help produce the other screens". "The way we can find certain characteristics from just one screen". "Integrating them all together to see how they inter-relate". "It makes understanding of the system much clearer". "The fact that it allows you to analyse a circuit independent of the circuit components and gives you a deeper understanding of how the system will react."

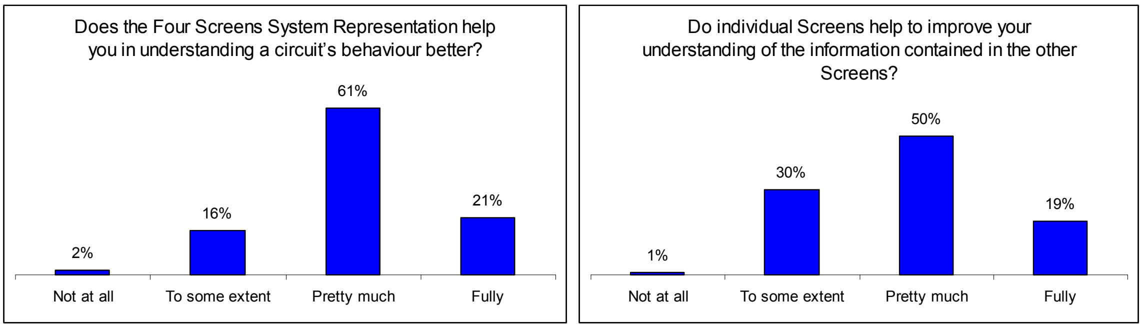

Figure 8: Some of 2004-2007 student questionnaire responses

The responses depicted in Figure 8, as well as student written statements show that students generally considered the Four-Screen approach to be helpful to their learning. Some noncommittal responses in Figure 8 may be attributed to cases where students have not reached adequate mastery of the representations of system behaviour.

Student abilities in working with all four screens were often not uniform, but the incidence of overlooking important representations was greatly reduced. Students appeared better motivated to present acceptable diagrams for all four screens, rather than overlooking some. In general, students’ capabilities as electronic designers have been enhanced.

Future Direction: Four Screen Interactive Model

4Screens web-based simulator

A student group developed this simulator over 2004-05. It became fully functional early in 2006, generating three screens of the Four Screen System Representation from inputs supplied in either Screen 1 or Screen 2. Figure 9 depicts the 4screens web-based simulator interface.

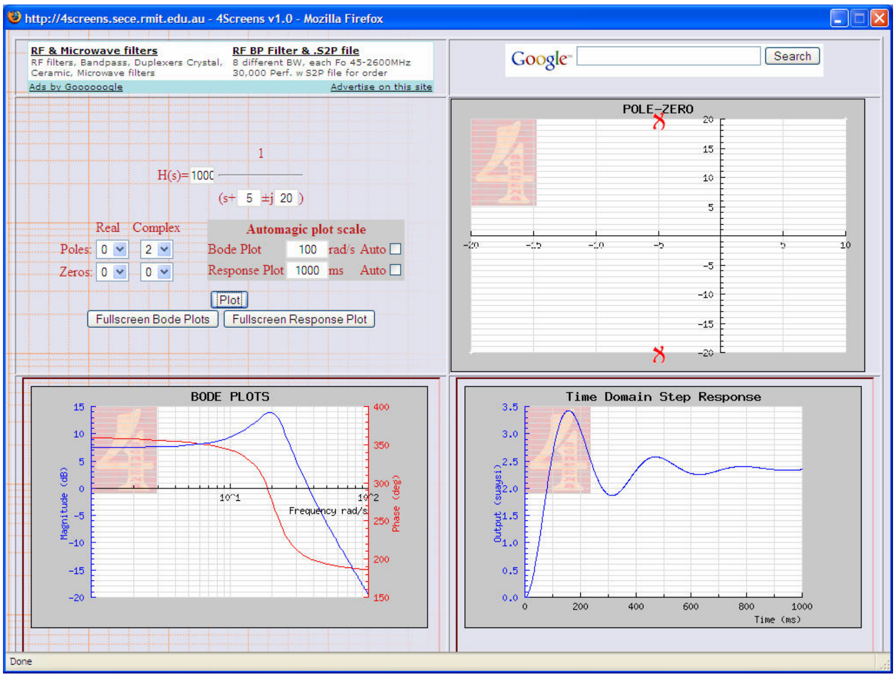

Figure 9: Web-based 4screens simulator (http://4screens.sece.rmit.edu.au)

A user first enters the number of system poles and zeros in Screen 1. He can then either enter their frequencies in Screen 1, or drag and drop them in Screen 2. Screens 1 and 2 mutually update automatically. Pressing the ‘Plot’ button invokes Bode plots and the step response. The Help facility provides additional functions.

The simulator was offered to students in 2006 and 2007 as an additional resource. They were regularly reminded to consider using the simulator to check their predictions of system behaviour. Usage of the 4Screens web-based simulator was compulsory only as a part of the second PSpice assignment. It had to be used to confirm the results of the PSpice simulation. Figure 10 shows the opinions of 87 student of the 4Screens web-based simulator.

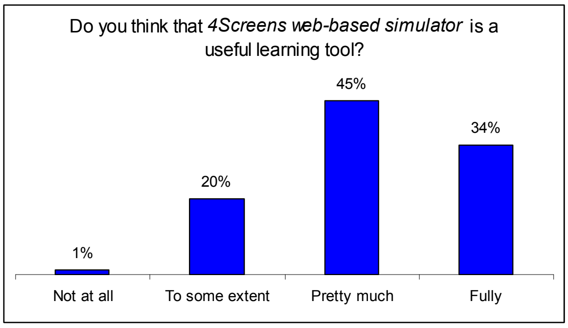

Figure 10: Student opinions of the 4Screens web-based simulator

The 4Screens web-based simulator gained value through students' ability to interact with it, supported by the computer doing the calculations. Many students liked the ability to quickly 'draw' all the four screens to check system's behaviour. Most of them suggested deploying the tool in the course more extensively.

Conclusion

Focussing students' attention on the Four-Screen representation yields improvements in understanding and design capabilities. The approach is generally well-accepted by students as evidenced by the questionnaire responses and the observed improvements in learning. Students work more effectively with the four screens, especially when these are supported by adequate background and practice materials. The Four-Screen representation enlivens the learning experience and it forms a suitable basis for exploratory approaches to design problems.

Experiences with teaching the Four-Screen representation continue to indicate that analogous approaches are likely to succeed in teaching and learning for other branches of engineering. The concepts also have direct relevance to mechanical and electro-mechanical systems with feedback, which are governed by similar differential equations (Belski (2002)). These include vibrations, control systems and audio transducer systems.

It is of importance to unite the knowledge presented to students as separate modules and to help them with the ability to make a professional judgement of a 'street' even when they have been able to see the street only through one window.

References

Belski, I. (2002). Seven Steps to Systems Thinking. *Proceedings of the 13th Annual Conference and Convention, Australian Association of Engineering Educators* (pp. 33-39). Canberra, Australia: AaeE.

Belski, I. & Gray, C. (2003). Four-Screen Representation of Electronic Systems. In C. Finelli, J. Froyd & S. Seidman (Eds.), *FIE Conference Proceedings* (pp. T4E7-10), Champaign IL: Stipes Publishing LLC.

Nilsson, J.W. (1983). *Electric Circuits.* Reading MA: Addison-Wesley.

Sedra, A.S. & Smith, K.C. (1998). *Microelectronic Circuits.* New York NY: Oxford University Press.

Acknowledgements

The authors wish to thank Mr. Peter Burton for his interest and for useful discussions.

Copyright statement

Copyright © 2007 I. Belski and D.C. Gray: The authors assign to AaeE and educational non-profit institutions a non-exclusive licence to use this document for personal use and in courses of instruction provided that the article is used in full and this copyright statement is reproduced. The authors also grant a non-exclusive licence to AaeE to publish this document in full on the World Wide Web (prime sites and mirrors) on CD-ROM and in printed form within the AaeE 2007 conference proceedings. Any other usage is prohibited without the express permission of the authors.