AC 2010-240: ROLE AND PLACE OF INTERACTIVE LEARNING MATERIALS IN AN UNDERGRADUATE INTRODUCTORY ECE CLASS FOR NON-MAJORS

Sergey Makarov, Worcester Polytechnic Institute

Sergey N. Makarov (M'98–SM'06) earned his B.S./M.S./Ph.D./Dr. Sci. degrees at the St. Petersburg (Leningrad) State University, Russian Federation – Department of Mathematics and Mechanics where he became a professor in 1996 – the youngest full professor of the Faculty. In 2000 he joined the Faculty in the Department of Electrical and Computer Engineering at Worcester Polytechnic Institute, MA where he became a professor and director of the Center for Electromagnetic Modeling and Design at WPI in 2008. His current areas of interest include electromagnetics, semiconductor device theory, and educational aspects of basic circuit theory.

Reinhold Ludwig, Worcester Polytechnic Institute

Reinhold N. Ludwig is a Professor with the Department of Electrical and Computer Engineering at Worcester Polytechnic Institute, Worcester, MA. He received his MSEE degree from the University of Wuppertal, Germany, in 1983 and his Ph.D. degree in electrical engineering from Colorado State University, Ft. Collins, CO, in 1986. Dr. Ludwig is a member of various professional societies, notably ISMRM, IEEE, Eta Kappa Nu, Sigma Xi, and ASNT. His research interests include RF circuit design, medical imaging, and nondestructive evaluation. His teaching interests include basic electromagnetic classes.

Stephen Bitar, Worcester Polytechnic Institute

Stephen J. Bitar is currently an Adjunct Instructor with the Department of Electrical & Computer Engineering at Worcester Polytechnic Institute in Worcester, MA. He received both his B.S. and M.S. degree in Electrical Engineering from WPI in 1981 and 1994 respectively. He has worked as an analog design engineer for several large companies including GE, Raytheon and Toshiba, as well as spending a decade working with automotive electronics and emission control systems. He has also worked as an electronic consultant in the area of power electronics. He is a member of IEEE and ASEE. His current areas of interest include analog electronics, pulse-width modulation applications and engineering education.

Role and place of interactive learning materials in an undergraduate introductory ECE class for non-majors

Most electrical and computer engineering departments in the United States and abroad typically offer a fundamental one or two-semester course in basic circuits for non-major students. Those classes typically have a large student population and they have increasingly become a recruiting tool of new ECE majors, or students interested in pursuing a minor in ECE. This paper reports on our method of teaching such a class that is particularly appealing to non-major students.

In this paper we would like to share our experience thus far with colleagues who are teaching similar non-major classes. We intend to discuss the following traditional and rather non-traditional topics:

1. Analogies to mechanical engineering concepts
2. Current flow in DC circuits
3. Basic semiconductor (diode) theory - is it difficult?
4. Basic solar cell and thermoelectric engine
5. Laboratory materials
6. MATLAB and LabVIEW
7. Historical context
8. Video tutorials
9. Conclusions and assessment

1. Analogies to mechanical engineering concepts

In our experience, analogies are most easily understood when discussed in a fluid mechanics context. Despite their well-known nature, the analogies are extremely useful in class, either drawn on a blackboard or shown on slides. Our approach of using fluid flow analogy starts with the first lecture; this often sets a positive bias that lasts throughout the entire class. These analogies are frequently listed in a number of standard texts for non-majors [1]-[4]. Therefore, they will not be reviewed here.

2. Current flow in DC circuits

Once the idea of fluid flow analogy is firmly established, it is beneficial for students to emphasize the current flow in various DC circuits: voltage and current dividers, transistor switches, and amplifiers. This becomes especially important when studying operational amplifiers, where the current path to the voltage supply and the role of the voltage supply itself are frequently ignored by some students.

Fig. 1 illustrates the current flow in a typical dual-rail amplifier. Fig. 1a) corresponds to the push mode - the non-inverting amplifier sources the current from the power supply. Fig. 1b) corresponds to the pull mode - the non-inverting amplifier sinks the current into the power source. Such a figure attracts close class attention and allows students to reflect on initial amplifier concepts. In particular, it clearly establishes the role of the dual power supply and the power rails for the amplifier. We again note that many non-major (as well as freshmen major) students quite often forget to power the amplifier in the laboratory. This is a very typical mistake that should be explained in class from the very beginning of the amplifier topic. The same strategy is applicable to a push-pull transistor amplifier.

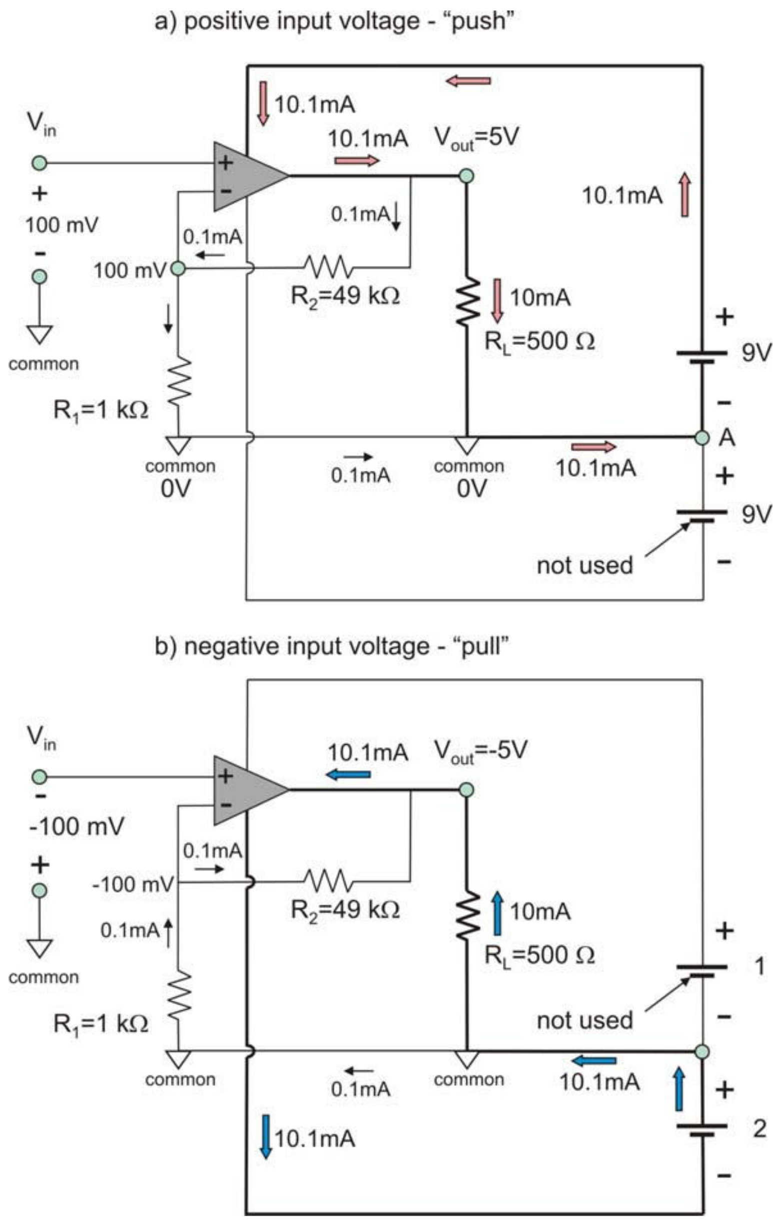

Fig. 1. Current flow in a non-inverting amplifier operating in a) push mode, and b) pull mode. The path of the load current is marked in bold. The same concept applies to the push-pull transistor amplifiers (when studied in class).

3. Basic semiconductor (diode) theory - is it difficult?

Should the diode theory be taught in a non-major class? The coverage of this rather non-traditional topic depends on the organization of the class curriculum and the personal interest of the instructor. According to our experience minimum *three* lectures would be necessary to understand the pn-junction diode concept. These three lectures may in particular cover:

1. Ideal diode model and the ideal pn-junction of two materials with opposite carrier types;
2. Boltzmann distribution and the built-in voltage of a pn-junction;
3. Shockley equation.

One should clearly realize that the Shockley and the built-in diode voltage are not the results of a quantum theory, but a direct combination of two classic disciplines: electrostatics and kinetic theory of an ideal gas of charge carriers. The built-in voltage of the diode pn-junction, the pn-junction Shockley equation, the solar cell operation, the thermoelectric engine operation, etc. can be conveniently explained, even in a non-major class, if the concept of an ideal electron gas and the related Boltzmann distribution are understood. Unfortunately, most mechanical engineering (ME) or biomedical engineering (BM) students do possess the background in the Boltzmann (or Maxwell-Boltzmann) statistics. This includes many fellow ECE students as well.

One way to familiarize non-major students with the Boltzmann statistics is to discuss the basic kinetic of compressible ideal gas in fluid mechanics, as originally developed in the 19th century, in class. It is interesting to note that only *after* it was established in mechanical engineering was it ultimately adopted by electrical engineers; they subsequently applied it to an "ideal gas" of free charge carriers in semiconductors. As a result, mechanical engineers are convinced by the instructor to have a *better* understanding of this concept as it is inherently a mechanical entity.

With this encouraging introduction we can now present the classical Boltzmann distribution following the kinetic theory: the number of particles per unit volume having kinetic thermal energy greater than or equal to $E_T \sim m\upsilon_T/2$ at temperature T and at any location x is given by

$$p(x) = p_0 \exp\left(-\frac{E_T}{kT}\right) \tag{1}$$

where p_0 is the undisturbed concentration (when particles with all energies and all "speeds" are present) and k is the Boltzmann constant, k=1.38066×10^{-23}J/K. The implication of Eq. (1) can be enhanced by a number of relevant examples given in class. Some of them may be quite funny.

As a next step, Eq. (1) is then applied to the carrier distribution in semiconductors. We keep in mind that the concentration of charge carries able to overcome the potential hill of $\Delta\varphi$ is given by Eq. (1), if $E_T = q\Delta\varphi$. This readily leads to the carrier distribution in a doped semiconductor subject to a built-in electric field due to a depletion layer, or due to an external electric field, or both, and enables us to link to all related results mentioned at the beginning of this section.

Along with Eq. (1) we need to introduce the mass-action law for carrier concentrations:

$$pn = n_i^2 \tag{2}$$

Eq. (2) should be clear based on our students' background from introductory chemistry classes.

Even though the careful introduction of Eqs. (1) and (2) consumes at least one lecture, the benefits of this mechanical-electrical approach are significant. We are now in a position to really *explain* a diode, Shockley equation, a pn-junction solar, a thermoelectric engine, and, if necessary, a junction transistor, and MOSFET channel inversion concept in the long run. We do not need Fermi energy levels for this introductory explanation, but may mention their importance for an in-depth professional study.

The present basic approach to semiconductor devices may become even more important in light of an increased interest in green energy and in particular solar energy and other semiconductor energy-converting devices. In addition, it permits us to reshape a significant part of the non-major class material as part of a "green-energy" class. Another relevant point of interest is the fast growing use of semiconductor LED sources.

4. Basic solar cell and thermoelectric engine

Once three-four lectures have been spent for the diode (including the diode rectifier and voltage regulator) we could spend other three-four lectures covering the solar cell and the (inverse) Peltier device (the thermoelectric engine). Those two devices are fundamental for semiconductor green energy generation. We are able to explain the equivalent circuit of the cell/module, the fill factor of the cell/module (readings on the back of the panel), and briefly explain the solar panel efficiency.

To make the semiconductor behavior easily accessible, the *electric potential approach* shall be adopted, which was introduced by Gummel *et al* yet in 60s-70s . We must avoid using quantum energy levels. In general, students feel quite comfortable with such an approach since they can rely on their freshman physics classes. Students can acquire an understanding of the solar cell operation and the related equivalent circuit based on this potential approach, see Fig. 2.

Time permitting, a similar approach is applied to a thermoelectric engine - see Fig. 3. Thermoelectric engines are alternative semiconductor-based or semiconducting oxide-based electric power devices that convert thermal power *directly* to electricity. Instead of the sunlight as for the solar cells, only the *temperature difference* between two sides of the device is needed to create electric power - see Fig. 3. This is a tremendous advantage of such a device, which in principle could be used anywhere where the steady-state temperature gradient is available. Unfortunately, the efficiency of such a device is extremely low at small temperature differences.

The conventional thermoelectric engine shown in Fig. 3 operates based on the *inverse* Peltier effect and uses either the *semiconductors* like SiGe or temperature-stable *semiconducting oxides* such as cuprous oxide, zinc oxide, etc. Two semiconductor or semiconducting oxide blocks shown in Fig. 3 have either p or n free charge carriers. Under the effect of a temperature gradient a steady-state diffusion of carriers starts from the hotter metal contact to the colder one. This diffusion is very similar to motion of molecules of an ideal gas from the area with a higher temperature to an area with a lower temperature. Consequently, the gas in the area with a higher temperature is rarefied while maintaining the same pressure over the entire volume.

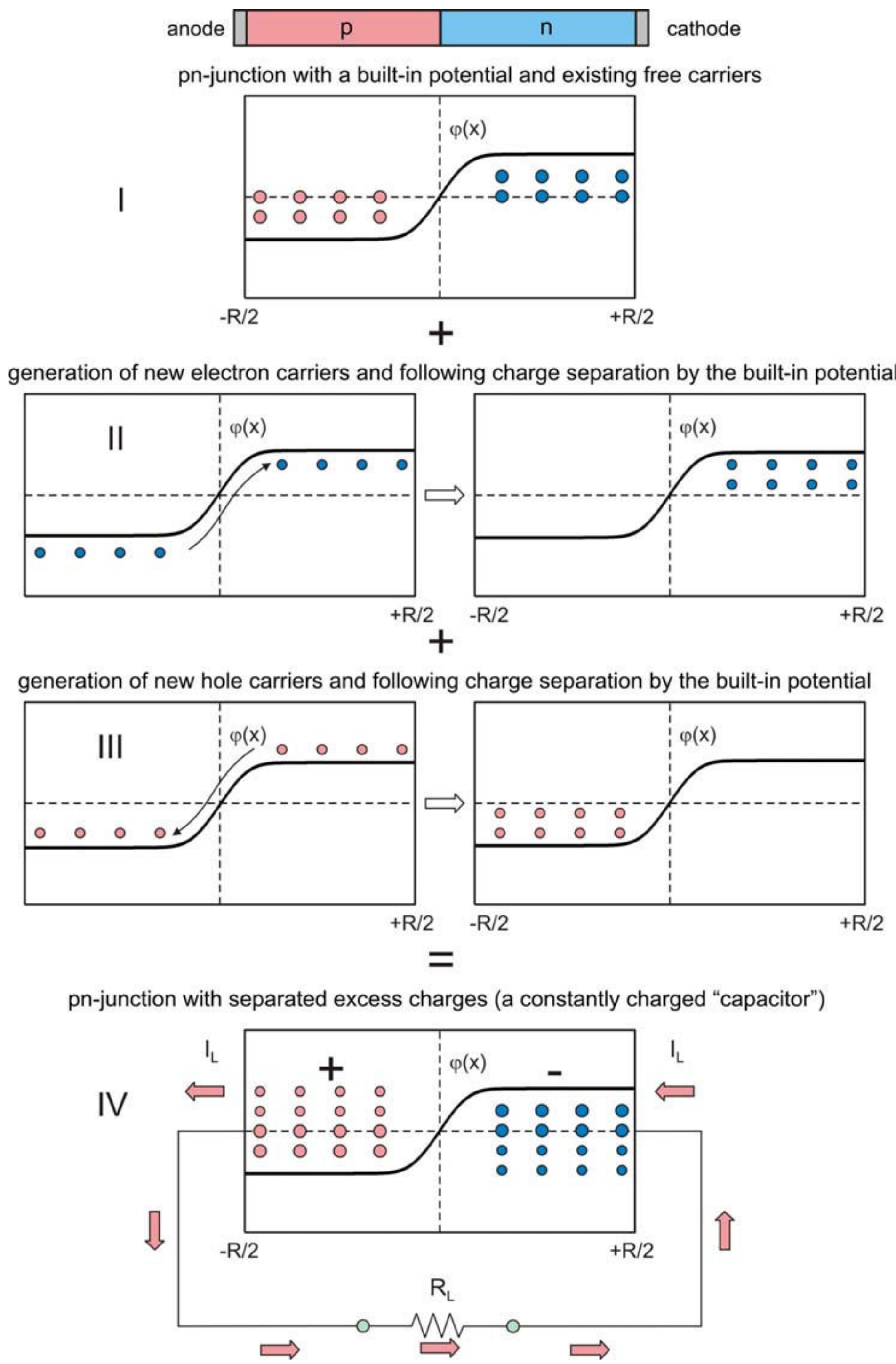

Fig. 2. Solar cell operation. The concept requires knowledge of the built-in electric potential $\varphi(x)$ of a pn-junction. I – III: separation of new charge carriers (created by an incident light source) with the help of the built-in potential in the pn-junction solar cell; IV: connecting the resulting charged "capacitor" to a load. Note to students: the charge separation mechanism is *common* for other electric sources including a battery (where it is accomplished by chemical reactions) and an electric generator.

The thermal diffusion of holes (positive carriers) creates the electric current directed down in Fig. 3-right. But the diffusion of electrons creates the electric current directed up in Fig. 3-left since the current direction is opposite to the direction of electron motion. Hence, the net current forms a closed loop through the thermoelectric engine as shown in Fig. 3. A load may be inserted in that current loop anywhere along the lower metal plate. To do so, we must break this plate, indeed. Thermoelectric engines currently are going down in price; they might perhaps become competitors to the solar cells in certain applications. Even though this subject may not be covered in a separate lecture, it is a viable subtopic of an inexpensive ($15 per bench) laboratory subproject.

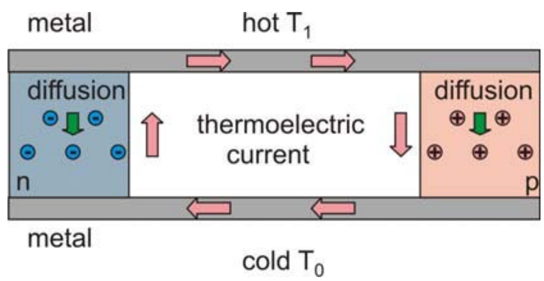

Fig. 3. Concept of the thermoelectric engine or an inverse Peltier device. Electric current due to thermal diffusion of opposite charge carriers forms a closed loop.

The sketch of the corresponding laboratory project (solar cell + Peltier device) is given below:
Introduction
Part I Equivalent circuit of the solar cell
1. A very primitive photovoltaic source (a LED)
2. Equivalent circuit of the solar cell (measure LEDs in series/parallel with the DMM)

Part II Single solar cell versus solar panel
1. Measuring solar cell geometry parameters - a 1-3W c-Si solar panel (~$25 per bench)
2. Solar cell performance at the laboratory bench
    a. Preparation of solar panel contacts
    b. Measuring open-circuit voltage and short-circuit current
    c. How much power do we really have?
    d. Using an electric energy storage element (capacitor) with the solar cell

Part III Solar panel and its efficiency (using an artificial light source)
1. Load matching (maximum power output)
2. Motor load
3. Efficiency of your module and to date efficiency of a c-Si solar module

Part IV Thermoelectric engine
1. Concept
2. Use
3. Effect of a higher temperature gradient

5. Laboratory materials

Class laboratory should be simple and practical. Under practical we imply that a laboratory project should have a clear, immediate relevance, at least by the end of the laboratory period.

Furthermore, the projects should directly support ongoing lectures, and vice versa. As an example, we would like to discuss three experiments. The first involves a simple qualitative experiment related to AC circuits, specifically to AC current dividers. A bypass capacitor inserted in shunt to a load forms a current divider circuit. Its effect is a shorting of the high-frequency AC signal (noise) across the load. Fig. 4 shows an example with a DC motor as a source of high-frequency noise, and the corresponding effect of the bypass capacitor. All laboratory components including a 0.7W motor can be procured for approximately $6.

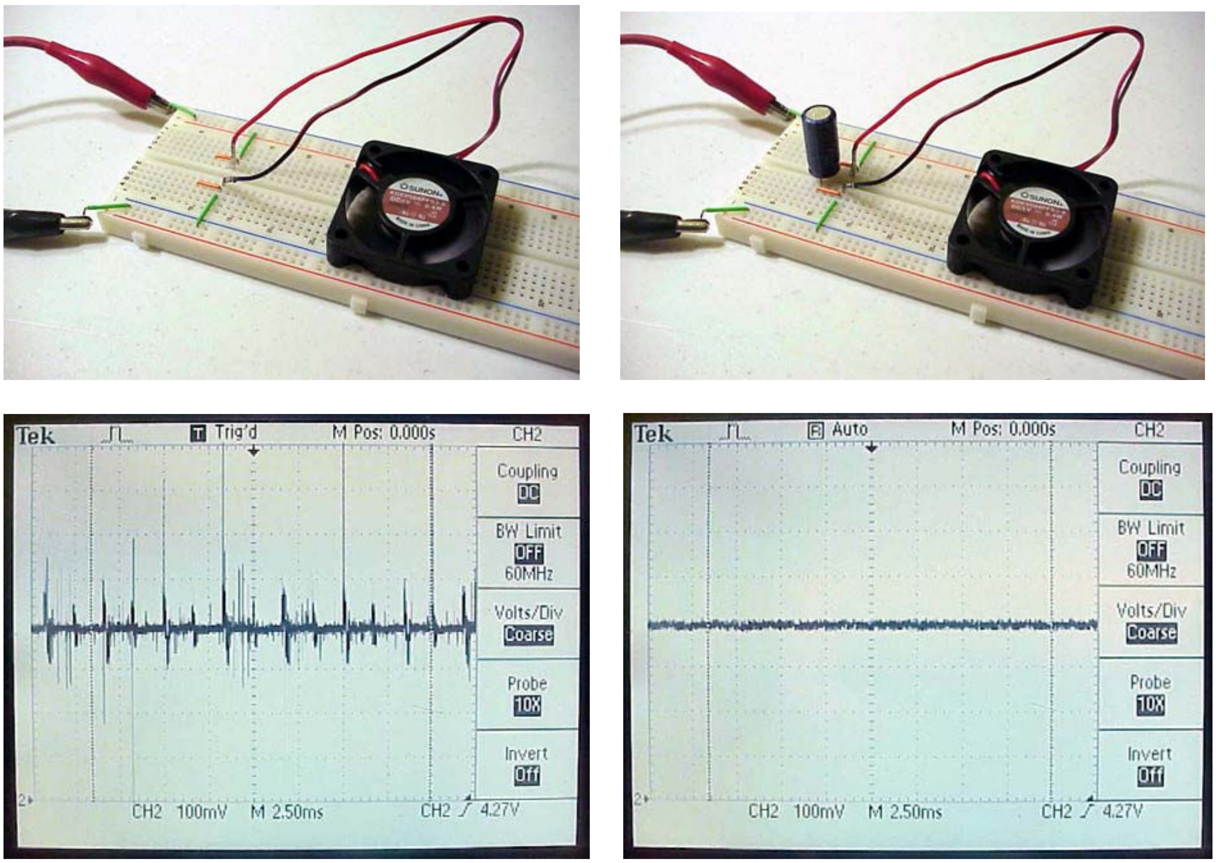

Fig. 4. A brief experiment showing the effect of a bypass capacitor in shunt to a load (DC motor). The capacitor plays a role of the short circuit for AC.

A number of such experiments (e.g. a bypass capacitor and an inductor choke) can be developed during the laboratory period. In particular, the second experiment may study the role of an inductor as an open circuit for AC (the role of the inductor isolator choke) - see Fig. 5. A 100 kHz AC source with the voltage amplitude of 2V (a 50Ω function generator) is connected to a 51Ω load resistor along with a 5V DC laboratory supply. The load voltage (a combination of AC and DC) is shown on the right. There is no inductor choke in the circuit on top. As a result, the AC signal is almost entirely shorted out by the DC power supply. In the center circuit, an inductor choke of 15μH used; the AC signal across the load becomes apparent. In the bottom circuit, an inductor choke of 10 mH is used. The AC signal amplitude is close to the desired 2V (the observed difference is due to inductor's series resistance)- the inductor blocks the AC current from leaking.

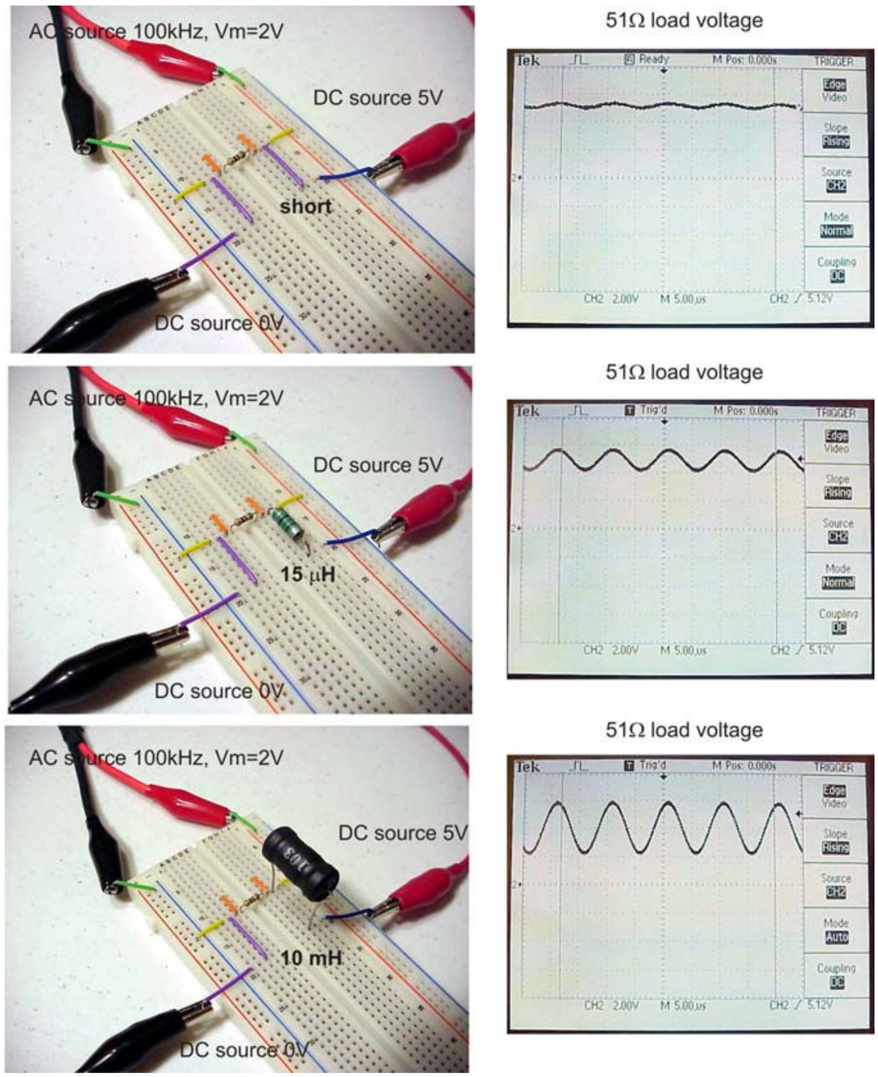

Fig. 5. A 100 kHz AC source with the voltage amplitude of 2V (50Ω function generator) is connected to a 51Ω load resistor along with a 5V DC laboratory supply. The load voltage (a combination of AC and DC) is shown on the right. There is no inductor choke in the circuit on top. As a result, the AC signal is almost entirely shorted out by the DC power supply. In the center circuit, an inductor choke of 15µH used; the AC signal across the load becomes apparent. In the bottom circuit, an inductor choke of 10 mH is used. The AC signal amplitude is close to the desired 2V - the inductor blocks the AC current

The third experiment relates to an instrumentation amplifier. We ask students to build and measure the voltage in a Wheatstone bridge that features a uniaxial strain gauge, and observe if they can bend a thick aluminum slab far enough to observe voltage variations on the oscilloscope. There are not many who succeed. Next, an instrumentation amplifier is built on the same protoboard and connected to the bridge. The complete circuit leads to variations of approximately ±2V at the output. Optionally, diode indicators can be connected to the output, as seen in Fig. 6. All laboratory components including a 350Ω strain gauge cost about $12.

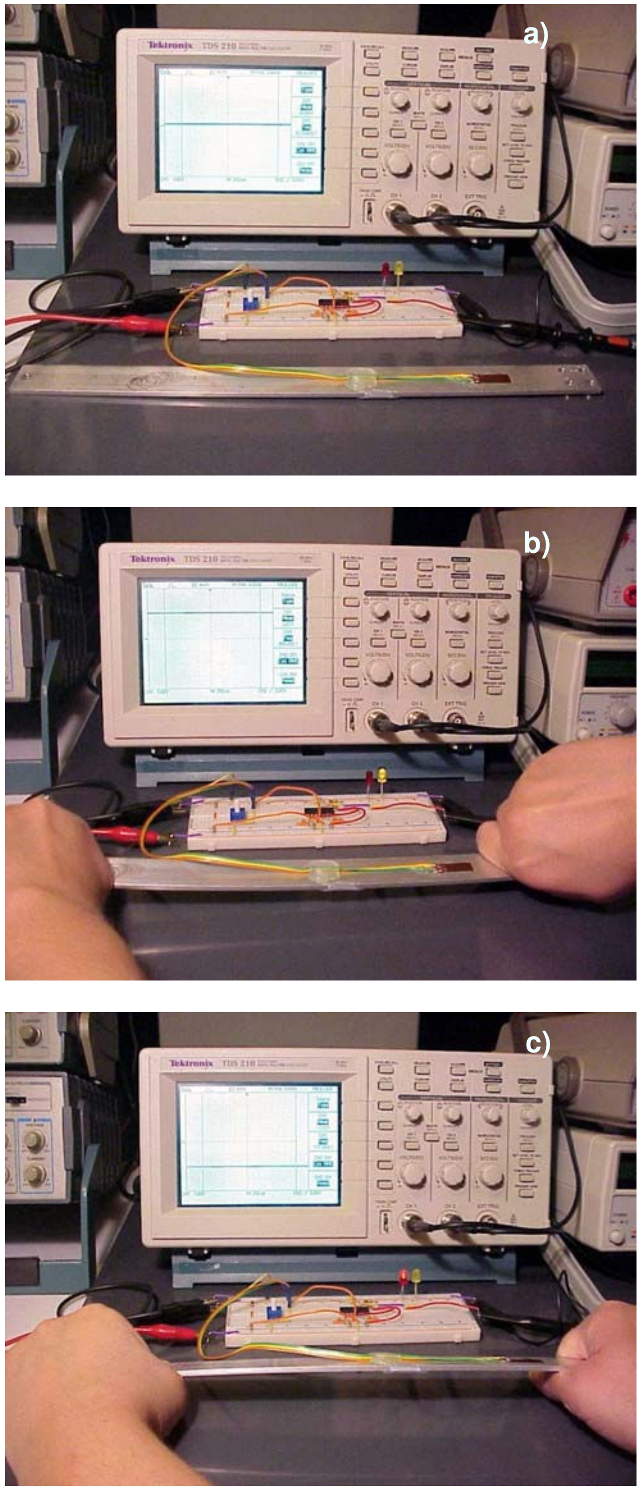

Fig. 6. Operation of the instrumentation amplifier with an attached strain gauge placed on an aluminum slab. The circuit is in front of the oscilloscope. The Wheatstone bridge is on the left portion of the protoboard; the amplifier IC is in the middle. a) - No strain; b) - a "positive" bending moment is applied; c) - a "negative" bending moment is applied. The oscilloscope resolution is 1V per division in each case.

6. MATLAB and LabVIEW

We support MATLAB as an interdisciplinary engineering language by assigning short MATLAB exercises as homework problems and, more important, as regular pre-lab or post-lab assignments. We do not teach MATLAB in class, but rather demonstrate its use. A basic example can be found in the class text or in a laboratory handout. Typically, students need to modify this example in order to accomplish the task. The following example directly copied from the laboratory handout, demonstrates the concept.

Laboratory #5 Part V MATLAB Postlab

To date, the average electricity consumption of the USA is approximately 5×10^{11} W. A beginner engineer estimates the size of a square area <u>in the state of New Mexico</u> to be covered with c-Si solar cells or with a-Si solar cells in order to fulfill this need. The engineer intends to check all possible square areas from 1 to 150 miles in width, as well as all possible efficiencies from 1 to 25%. After that he/she would like to create a contour plot in order to observe how does the required area increase/decrease depending on available efficiency.

An older and more experienced colleague from the same company has already started a MATLAB script for that purpose, which is given below. However, this colleague made at least one critical mistake, and misspelled some MATLAB command(s):

```
clear all;
close all;
%-------------------------------------------------------
%   Array of available area widths (a 1D array of numbers)
Wmiles  = [1:1:150];         %   width of the square area in miles  (vector)
Wmeters = Wmiles*1609;       %   width of the square area in meters (vector)
A   =  Wmeters.*Wmeters;     %   area in m^2 (vector); note element-by-element
                             %   vector multiplication!
%-------------------------------------------------------
%   Array of available array efficiencies (a 1D array of numbers)
E   = [1:1:25;              %   efficiency percentage (vector)
%-------------------------------------------------------
%   Matrix of all available total output powers of the array (a 2D array of numbers)
p   = 1000;                  %   average daily solar radiation in W per m^2 (scalar)
for i = 1:length(A)
    for j = 1:
        P(i,j) = p*A(i)*E(j)*0.01;  %   total average daily power of the array (matrix)
    end
end
%-------------------------------------------------------
%   "Plot" the matrix - a contour plot of all available total output powers
v     = [50 100 200 500 1000];    %   create contour plot levels in Gigawatts
[C,h] = contour(P*1e-9, V);       %   create contour plot of output powers in Gigawatts
clabel(C,h);                      %   create contour plot labels
%clabel(C,h,'FontSize',12,'Color','r','Rotation',0); %   be fancy (do not have to)
grid on
```

<u>Your goal is:</u>

1. Find and fix all missing parts and/or bugs in the above script (7 points). You may want to use Appendix A and double check the number(s) used in the initial script.

2. Properly label axes, insert the grid, and insert the title (2 points). The x-axis should be the efficiency percentage, E; the y-axis should be the width of the square area in miles, W.
3. Print the corrected MATLAB script, and also print the corresponding contour plot.
4. In the contour plot, shade with a pencil the region of all possible pairs (E, W) that give the average electric output of the array greater than or equal to the current USA electric consumption of 5×10^{11} W (1 point).

We also support LabVIEW depending on the current hardware availability (NI DAQs).

7. Historical context

As time permits (especially during a Friday lecture) we include short excursions into the history and background of the discussed topic. Our custom materials used in class have a large number of such examples involving such icons as Heaviside, Edison, Tesla, Marconi, Bell, Shockley, Kilby, Noyce, and many others. One less-known example is related to the invention of the negative-feedback amplifier by a WPI graduate, Harold S. Black. The original New York Times page and a page from a control textbook is shown in Fig. 7.

Harold S. Black graduated from Worcester Polytechnic Institute in 1921 and joined Bell Laboratories of American Telegraph and Telephone (AT&T). In 1921, the major task confronting Bell Labs was the improvement of the telephone system and the design of improved signal amplifiers. Black was assigned the task of linearizing, stabilizing, and improving the amplifiers that were used in tandem to carry conversations over distances of several thousand miles.

Black reports [8]:

> Then came the morning of Tuesday, August 2, 1927, when the concept of the negative feedback amplifier came to me in a flash while I was crossing the Hudson River on the Lackawanna Ferry, on my way to work. For more than 50 years I have pondered how and why the idea came, and I can't say any more today than I could that morning. All I know is that after several years of hard work on the problem, I suddenly realized that if I fed the amplifier output back to the input, in reverse phase, and kept the device from oscillating (singing, as we called it then), I would have exactly what I wanted: a means of canceling out the distortion in the output. I opened my morning newspaper and on a page of *The New York Times* I sketched a simple canonical diagram of a negative feedback amplifier plus the equations for the amplification with feedback. I signed the sketch, and 20 minutes later, when I reached the laboratory at 463 West Street, it was witnessed, understood, and signed by the late Earl C. Blessing.

Fig. 7. Left: A note from the text of Richard C. Dorf and Robert H. Bishop, *Modern Control Systems*, Prentice Hall, 2001, 9th edition. p. 7. Right: a page of The New York Times - the birthplace of a negative-feedback amplifier (Bell Labs Museum).

8. Video tutorials

The textbook by Hambley [1] was adopted for the class over a long period of time. We have recently switched to a similar custom text that makes extensive use of video tutorials. It has been our experience that "the more videos, the better". Our class currently features twenty-three such 5-min tutorials recorded with Echo360 and devoted to key class concepts. Fig. 8 shows the corresponding format.

All tutorials are posted on the local class's website and suggested as extra help for homework reading and preparation. Sometimes, it helps to assign one or two specific video tutorials for each lecture. It is our experience that a class website equipped with a full set of tutorials immediately makes the class body more organized and appealing.

According to the "statistics tracking" recording option, the tutorials are generally viewed by as many as 50% of students signed up at the beginning of the class.

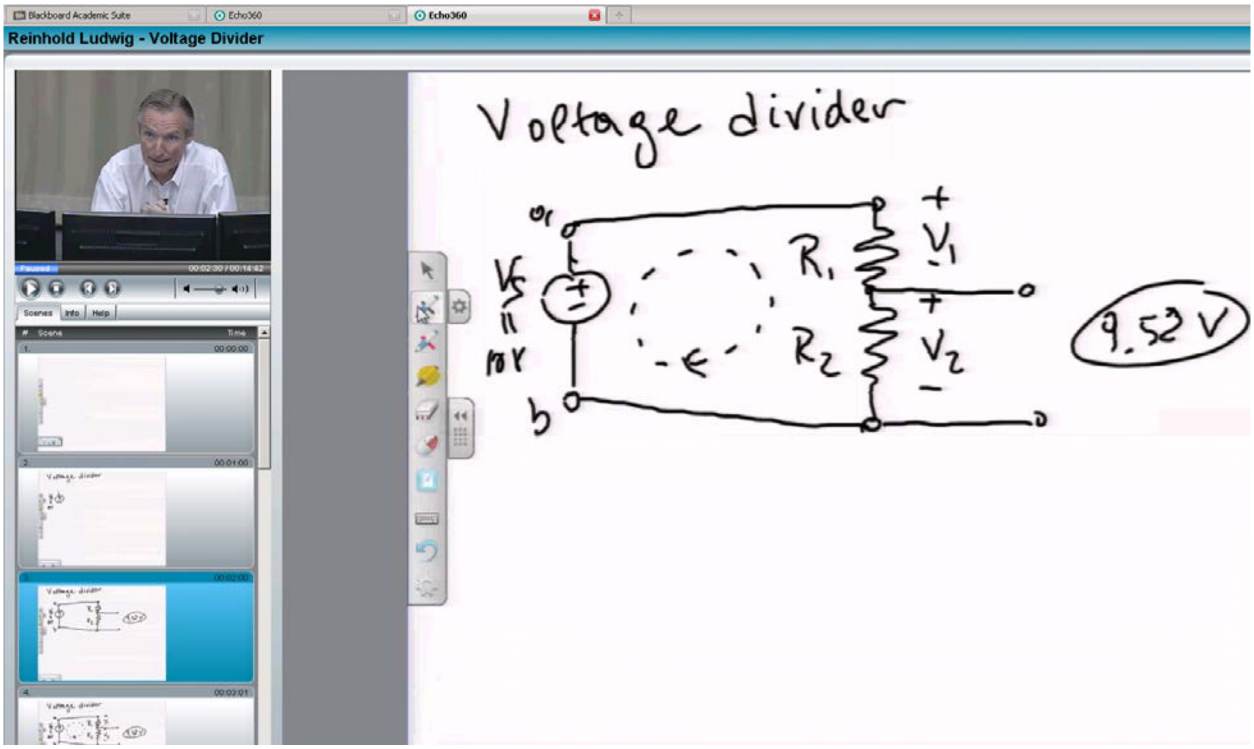

Fig. 8. Format of a 5 min-long class tutorial. The presentation is captured about 3 minutes from the start of the video.

10. Conclusions and assessment

Certain elements of our classroom teaching strategy can easily be adopted by professors and instructors who are assigned to teach introductory ECE classes for non-majors. Over the past eight years the presented approach has created a relatively high level of student interest and has resulted in consistently high class evaluations. Furthermore, the approach has also created an interest and support among the non-ECE engineering professors.

As an example, Table 1 lists the student assessment (case in point - *stimulation of interest in the ECE*) for three comparable consecutive classes (Spring terms of 2007-2009, juniors and seniors) with nearly 130 students each.

Table 1. Assessment results for three nearly identical non-major classes with circa 130 students each (Spring of 2007-2009). Grade from 0 to 5.00.

	Spring 2006-2007	Spring 2007-2008	Spring 2008-2009
The instructor stimulated my interest in the subject matter (compared to other classes)	4.09	4.21	4.46

The most controversial issue is whether or not to include the green energy-related materials into a non-major class given its very tight curriculum. As an example, Table 2 given below presents evaluation results for the same non-major class with nearly the same student enrollment (about 70+ students) taught at our school during two academic years of 2007-2009 (Fall semester) with (Course #1) or without (Course #2) the green energy content. The result speaks for itself. However, in the first case, we had to introduce four new relevant lectures, slightly change the rest of the curriculum, and replace one laboratory project out of seven. This has been done at the expense of the motor-related part of the class, which may be a significant loss in the long run.

Table 2. Assessment results for two nearly identical non-major classes with circa 70 students with (Course#1) and without (Course #2) the green energy content - 2007-2009.

	Course #1 (Fall of 2009) Grade from 0 to 5.00	Course#2 (Fall of 2007) Grade from 0 to 5.00
The amount I learned from the course was (compared to other classes)	4.60	4.38
The instructor stimulated my interest in the subject matter (compared to other classes)	4.80	4.31

Arguably, the most important responses came from the alumni. These responses mostly confirmed not only the usefulness of the selected class topics (which can change from term to term and from year to year, indeed), but also provided greater interest in electrical and computer engineering. We will further refine our approach and report on these efforts in the future.

References

[1]. A. Hambley, *Electrical Engineering: Principles and Applications*, 5th Edition, Jan. 2010, Prentice Hall, Upper Saddle River, NJ, 912 p.

[2]. J. W. Nilsson and S. Riedel, *Electric Circuits*, 8th Edition, May 2007, Prentice Hall, Upper Saddle River, NJ, 880 p.

[3]. G. Rizzoni, *Fundamentals of Electrical Engineering*, 1st Edition, Feb. 8th 2008, McGraw-Hill, 736p.

[4]. R. C. Dorf and J. A. Svoboda, *Introduction to Electric Circuits*, 8th edition, Jan. 7th 2010, Wiley, New York, 886 p.