Deliberate Longitudinal Curricular Integration: Topical Linkages and Concept Reinforcement

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Abstract.

Students in many engineering programs feel that their educational experience consists of a series of isolated courses that build expertise in discrete topical areas. The only time these discrete topics are integrated is in a capstone engineering project during their senior year. Understanding how topics covered in one course relate to previous courses in the program would give students a better foundation on which to build their new knowledge. This paper describes the deliberate curriculum integration in the Electrical Engineering Program at the U.S. Military Academy in which topical linkages and recurring thematic examples are used to demonstrate course-to-course disciplinary linkages and reinforce foundational concepts as the student progresses through the program. For example, the integration effort strives to unify development of topics such as resonance, filtering, stability, transmission line behavior, and spectral characteristics of lasers in courses such as signals and systems, basic electric circuits, controls, electromagnetic fields, and photonics from mathematical models and analysis techniques associated with second-order linear system response describing damped harmonic oscillators. Recurring thematic examples provide opportunities for students to revisit familiar examples with new tools and look at these examples from a different perspective. They also provide opportunities to reinforce linkages throughout the curriculum thereby removing artificial topical boundaries.

1.0 Introduction.

Integration of curricular concepts is a topic that has received attention in various disciplines. Too often, students view graduation requirements as a series of individual courses that must be successfully negotiated to obtain a degree. Students often fail to appreciate the importance of linkages within and among courses and subjects, and instead view their undergraduate education as a series of disjoint and unrelated courses.

Making conceptual linkages and transferring knowledge from one context to another is a particularly important skill for engineers[1]. Engineers routinely are required to reduce complex problems to simpler ones that they can understand and analyze using well understood principles and models. Additionally, learning new information is more effective and efficient if the new information is framed within a known context and in fact, deduced from an established knowledge base. Deliberate integration of the curriculum that includes topical linkages and concept reinforcement is an effective means to assist engineering students make these conceptual linkages and transfer knowledge. It also lays an important foundation that helps them understand better how to learn and ultimately become life-long learners.

In 2000, the Association of American Colleges and Universities commissioned a two-year study to analyze the challenges facing higher education. In 2002, the National Panel Report: "Greater Expectations, A New Vision for Learning as a Nation Goes to College" provided additional insights to curriculum integration:

> The shape of the undergraduate curriculum was essentially fixed half a century ago. It combines a broad general education common to all students (usually completed in the first two years or out of sequence in later years), more specialized study (a major) to give deeper knowledge of a chosen field, and electives to suit students' individual interests. Although listed in the catalog as part of a curriculum, individual courses are effectively "owned" by departments, and most advanced courses by individual professors. Few faculty members teach to collectively owned goals. The student assembles an assortment of courses, each carrying a defined number of credits and assuming a standard time in class. The degree certifies completion of a fixed number of these often disconnected fragments. There is little internal coherence in curricula or programs, and even less a plan for connected learning …. The departmental structure reinforces the atomization of the curriculum by dividing knowledge into distinct fields, even though scholarship, learning, and life have no such artificial boundaries.[2]

We have experienced similar isolationism within the electrical engineering curriculum at West Point. Two years ago, we set-out to provide topical linkages both within individual courses and among courses in the curriculum in an attempt to remove the artificial barriers and to reinforce key foundational concepts. Integration of the curriculum begins by identifying common foundational themes within and between courses, and highlighting these to students as the topical coverage warrants. Deliberate integration of the curriculum is accomplished by not only identifying the foundational themes through conceptual abstraction, but also, by design of common exemplars. Reinforcing these concepts through recurring common examples helps the student better understand and master these concepts while simultaneously understanding the linkages between courses.

While many foundational concepts and threads can be identified within the electrical engineering discipline, we have selected one example to demonstrate the methodology by which we intend to achieve deliberate curricular integration through topical linkages and concept reinforcement – the concept of energy transfer modeled by second-order differential equations, and resulting in the damped harmonic oscillator.

2.0 Foundational Theme – Energy Transfer, the Second-Order Differential Equation, and the Damped Harmonic Oscillator.

The concept of energy transfer in electrical engineering is fundamental to understanding a wide range of concepts and applications. Even before students encounter energy transfer in electrical and electronic applications, they are introduced to energy transfer in physics through an analysis of mechanical systems. The physical transfer of energy among various storage elements is mathematically modeled by differential equations. First-order differential equations are used to characterize single energy storage elements such as springs, capacitors, and inductors. Second-order differential equations are used in applications with two storage elements and describe the interaction between these elements. Potential energy in a spring converted to kinetic energy in a mass through a viscous damper resistance mechanism is described by a second-order differential equation. The energy transfer from the electric field of a capacitor to the magnetic field of an inductor through the loss mechanism of a resistance is similarly described by a second-order differential equation. Likewise, the energy exchange between the electric and magnetic fields of a propagating electromagnetic wave is described by a second-order differential equation. Additionally, each of these applications exhibits classic damped harmonic oscillator behavior. Understanding this energy exchange mechanism provides important physical insights for students when considering spring-mass-damper mechanical systems, resistor, inductor, capacitor (RLC) electrical circuits, electromagnetic wave propagation in an unbounded medium or through a transmission line, and laser spectral characteristics, to name a few.

3.0 Mathematics Preparation.

When navigating the core educational requirements of most academic institutions, a student encounters differential calculus. Most mathematics texts begin the motivation of the derivative by discussing the analysis of tangents of curves. Many extend this concept to the application of velocity to provide a physical interpretation and application of the derivative. Some even mention examples of RC circuits, radioactive decay, continuously compounded interest, mixing of solutions, and the spread of epidemics[3]. Motivation for the second derivative normally comes in the form of analysis of curves, specifically inflection points and maxima and minima.

The solution to the second-order linear constant coefficient differential equation traditionally begins by considering the homogeneous equation of the general form,

$$a\frac{\mathrm{d}^2 y}{\mathrm{d}x^2} + b\frac{\mathrm{d}y}{\mathrm{d}x} + cy = 0\,, \qquad (1)$$

or, written more concisely,

$$a\ddot{y} + b\dot{y} + cy = 0\,. \qquad (2)$$

The student is asked what function and its higher-order derivatives have the same functional form, which motivates the selection of an exponential as the solution. Assuming a solution of the form

$$y = Ae^{\lambda t}\,, \qquad (3)$$

yields

$$Aa\lambda^2 e^{\lambda t} + Ab\lambda e^{\lambda t} + Ace^{\lambda t} = 0 \qquad \Rightarrow \quad Ae^{\lambda t}\left(a\lambda^2 + b\lambda + c\right) = 0\,. \qquad (4)$$

We are not interested in the trivial solution so $A \neq 0$ and $e^{\lambda t} \neq 0$ for any finite value t. Consequently, the student is introduced to the characteristic or auxiliary equation

$$\left(a\lambda^2 + b\lambda + c\right) = 0\,. \qquad (5)$$

From this characteristic equation, the student finds the roots and ultimately the solution of the homogeneous equation.

$$\lambda_1 = \frac{-b + \sqrt{b^2 - 4ac}}{2a}, \qquad \lambda_2 = \frac{-b - \sqrt{b^2 - 4ac}}{2a}\,. \qquad (6)$$

The roots of the characteristic equation determine the nature of the solution:

- Real and distinct roots produce: $y = C_1 e^{\lambda_1 t} + C_2 e^{\lambda_2 t}$
- Real and equal (repeated) roots produce: $y = C_1 e^{\lambda_1 t} + C_2 t e^{\lambda_1 t}$

– Complex roots:
$y = C_1 e^{\lambda_1 t} + C_2 e^{\lambda_2 t} = C_1 e^{rt} \cos \mu t + C_2 e^{rt} \sin \mu t$, where $\lambda_1 = r + j\mu$ and $\lambda_2 = r - j\mu$

For an applied forcing function, students proceed to find the particular solution after solving for the homogeneous solution.

The development of the solution to a second-order linear constant coefficient differential equation has far reaching and significant implications within the electrical engineering discipline. The exponential function selected as the assumed solution to the differential equation is, in fact, an eigenfunction of a linear time invariant (LTI) system. This concept is foundational in electrical and electronic system characterization and modeling. Additionally, as an eigenfunction of an LTI system, the complex exponential is the fundamental mathematical element in phasor analysis, which provides a method of finding sinusoidal steady-state responses directly from the circuit without using differential equations. The phasor may be regarded as the mathematical equivalent of a sinusoid with the time dependence dropped and has direct linkages to Fourier analysis in the frequency domain. The characteristic equation developed as part of the solution to the differential equation is equally important, providing insights into circuit and system behavior, such as stability and performance of filters and control systems.

4.0 Physics and Damped Harmonic Motion.

In introductory physics courses, the concepts of potential energy and kinetic energy are first introduced, followed by the concept of conservation of energy and simple harmonic oscillation. This introduction to energy storage and transfer usually follows from Newton's Laws. Specifically, since acceleration is the second derivative of position, Newton's Second Law, $F = Ma$, results in $F = M\ddot{x}$, which is used to describe simple harmonic motion and is readily extended to damped harmonic motion in the second-order spring-mass-damper problem, shown in **Figure 1**.

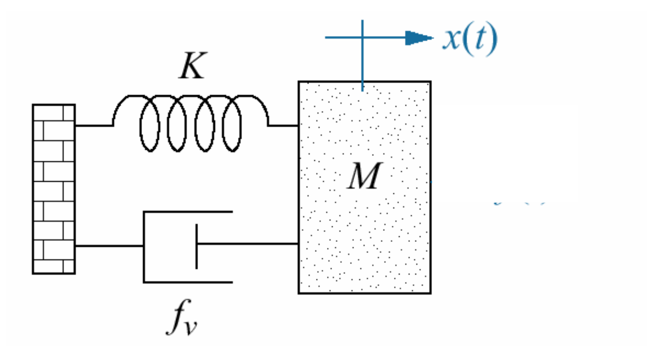

Figure 1. Spring, mass, damper problem.

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The force-velocity relationship for the spring in this application can be described as

$$f(t) = K\int_0^t v(\tau)\mathrm{d}\tau \,, \tag{7}$$

while the force-velocity relationship for the viscous damper is

$$f(t) = f_v v(t) \,, \tag{8}$$

and the force-velocity relationship for the mass is

$$f(t) = M \frac{dv(t)}{dt}. \tag{9}$$

These individual relationships can be combined to describe the equation of motion for this mechanical system as

$$M \frac{d^2x(t)}{dt^2} + f_v \frac{dx(t)}{dt} + Kx(t) = 0. \tag{10}$$

In this application, conservation of energy describes how potential energy in the spring and kinetic energy in the mass are exchanged periodically, while energy is dissipated continuously by the viscous damper. The solution to this equation of motion describes damped harmonic oscillation

$$x(t) = Ae^{-\alpha t}\cos(\omega_0 t + \phi), \tag{11}$$

where

$\alpha = f_v / 2M$ is the decay constant, $\omega_0 = \sqrt{\omega_n^2 - \alpha^2}$ is the damped angular frequency,

$\omega_n = \sqrt{K/M}$ is the undamped natural frequency, and A and ϕ are determined by the initial displacement and velocity. The resulting damped harmonic motion of this mechanical system is shown in Figure 2. This classic response is found in many applications and understanding the nature of its origin is foundational to energy transfer and second-order differential equations.

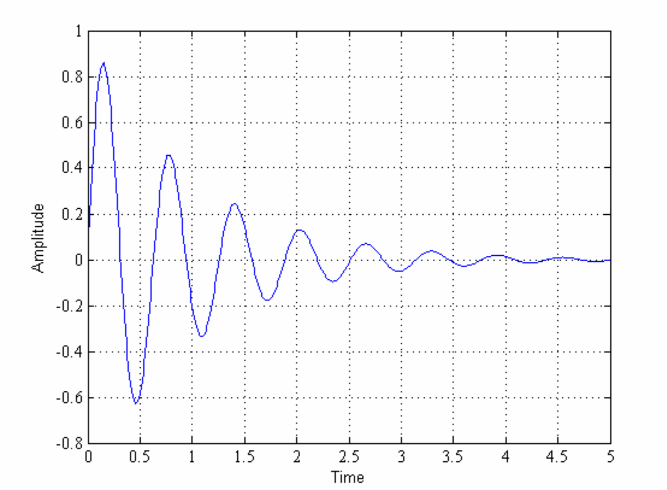

Figure 2. Damped harmonic motion of spring, mass, damper system.

5.0 The Electrical Engineering Curriculum at West Point.

The electrical engineering curriculum at West Point is comprised of a total of eighteen (18) courses beyond the core curriculum requirement, beginning in the second semester of sophomore year. To provide a frame of reference for the deliberate curricular integration discussed in this paper, Table 1 provides an overview of the electrical engineering curriculum. The blue courses represent the core electrical engineering courses, the yellow courses represent a 3-course depth sequence with a choice of robotics, communications, information assurance, computer architecture, or electronics. The orange courses are out-of-department breadth courses in mechanics, thermodynamics and fluids. One department elective is identified by the salmon color. The courses in the electrical engineering program at West Point are typical of those courses found in most undergraduate electrical engineering curricula and therefore the deliberate curricular integration approach described in this paper has wide application to other electrical engineering curricula. The extension of this approach to other disciplines and curricula is equally straightforward.

In what follows, we will reference the specific courses in which the deliberate curriculum integration occurs.

4th Class Freshman I	4th Class Freshman II	3rd Class Sophomore I	3rd Class Sophomore II	2nd Class Junior I	2nd Class Junior II	1st Class Senior I	1st Class Senior II
Chemistry	Chemistry	Philosophy	*EE360 Digital Logic*	*EE302 Intro to EE*	*EE362 Intro to Electronics*	*EE462 Electronics Design*	*EE400 Seminar*
Math	Math	MA205 - Calculus II	*MA364 Engineering Math*	*EE381 Signals & Systems*	*EE383 E&M Fields & Waves*	*EE401 Electronic System Design I*	*EE402 Electronic System Design II*
English	Literature	PH201 - Physics I	PH202 - Physics II	*EE375 Computer Architecture*	*EE Depth*	*EE Depth*	*EE Depth*
Info. Tech.	General Psych	Economics	Terrain Analysis	*ME311 Thermo-Fluids I*	*CE302 Statics & Dynamics*	*EE486 Solid State Electronics*	*Elective*
History	History	Foreign Language	Foreign Language	MA206 Probability & Statistics	International Relations	Military History I	Military History II
			American Politics	Advanced Composition	Leadership		Law

Table 1: The Electrical Engineering Curriculum at West Point.

6.0 Examples of Damped Harmonic Oscillation.

In the following sections, we provide examples of energy transfer, second-order differential equations, and the damped harmonic oscillator in core and elective electrical engineering courses in the Electrical Engineering Program at West Point.

6.1 Core Electrical Engineering Courses.

6.1.1 Engineering Mathematics.

Engineering mathematics focuses on the application of mathematical foundations to science and engineering problems. Emphasis is placed upon using mathematics to gain insight into natural and man-made phenomena that give rise to problems in differential equations and vector calculus. In MA364 during the first semester of their electrical engineering experience, students revisit the classical spring-mass-damper mechanical system they first encountered in physics.

They write the equation of motion, solve the differential equation using classical techniques and Laplace transforms, and use Mathematica to gain additional insights from the response to various forcing functions. Students also revisit electronic circuit analysis as well as other engineering applications of ordinary differential equations and classical partial differential equations. Calculus topics focus on three- dimensional space curves, vector fields and operations, divergence and curl, line and surface integrals. This is the first occurrence of deliberate curricular integration, reinforcing topical coverage of the second-order differential equations previously introduced in physics.

6.1.2 Introductory Electronic Circuit Analysis.

The Introduction to Electrical Engineering course, EE302, is the first course in circuit analysis. Students are introduced to the fundamental passive circuit elements, the resistor, capacitor, and inductor and they analyze circuits composed of these elements.

Understanding the dynamic behavior of RLC circuits is foundational to an electrical engineering education. After developing network analysis techniques with purely resistive elements, students are introduced to first-order, lumped-parameter, RL and RC circuits. We develop the concept of the time constant as a parameter that represents the behavior of the circuit in the time domain. We then introduce the second-order RLC circuit, such as the series RLC circuit shown in Figure 3. Just as the spring-mass-damper system converts potential energy into kinetic energy and vice-versa through a lossy element, the RLC circuit transfers energy stored in the capacitor's electric field to energy stored in the inductor's magnetic field through a lossy element, the resistor.

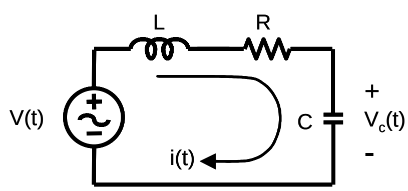

Figure 3: Series RLC Circuit

Applying Kirchhoff's Voltage Law (KVL) around the closed loop we get

$$L\frac{\mathrm{d}i(t)}{\mathrm{d}t} + Ri(t) + \frac{1}{C}\int_0^t i(\tau)\mathrm{d}\tau = v(t). \qquad (12)$$

Since current is related to the time rate of change of charge,

$$i(t) = \frac{\mathrm{d}q(t)}{\mathrm{d}t}\ , \qquad (13)$$

this equation can be rewritten as

$$L\frac{\mathrm{d}^2 q(t)}{\mathrm{d}t^2} + R\frac{\mathrm{d}q(t)}{\mathrm{d}t} + \frac{1}{C}q(t) = v(t). \qquad (14)$$

Finally, since

$$q(t) = Cv_c(t), \qquad (15)$$

we have

$$LC\frac{\mathrm{d}^2 v_c(t)}{\mathrm{d}t^2} + RC\frac{\mathrm{d}v_c(t)}{\mathrm{d}t} + v_c(t) = v(t). \qquad (16)$$

If we let $v(t) = 0$, we can find the homogenous solution, or the natural response of the circuit. Assuming

$$v_c(t) = e^{\lambda t}, \tag{17}$$

we have

$$LC\lambda^2 e^{\lambda t} + RC\lambda e^{\lambda t} + e^{\lambda t} = 0 \qquad \Rightarrow \quad e^{\lambda t}\left(LC\lambda^2 + RC\lambda + 1\right) = 0 \tag{18}$$

which results in the same form of the characteristic equation as shown in Equation (4),

$$\left(\lambda^2 + \frac{R}{L}\lambda + \frac{1}{LC}\right) = 0. \tag{19}$$

The roots of this characteristic equation are

$$\lambda = -\frac{R}{2L} \pm \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}. \tag{20}$$

The form of the roots of this characteristic equation determines the physical response of this circuit. The equation above is commonly represented in terms of a damping factor, α, and the undamped natural frequency, ω_n,

$$\lambda = -\alpha \pm \sqrt{\alpha^2 - \omega_n^2}, \tag{21}$$

where

$$\alpha = \frac{R}{2L} \qquad \omega_n = \frac{1}{\sqrt{LC}}. \tag{22}$$

The roots can be real and distinct, real and repeated, or complex conjugate pairs. Distinct real roots produce an overdamped response, repeated real roots produce a critically damped response, and a complex conjugate pair of roots produce an underdamped response, as shown in Table 2.

Case	**Circuit Parameters**	**Form of roots**	**Time domain response**
$\alpha > \omega_n$	$R > \frac{2L}{\sqrt{LC}}$	Real, distinct	Overdamped
$\alpha = \omega_n$	$R = \frac{2L}{\sqrt{LC}}$	Real, repeated	Critically damped
$\alpha < \omega_n$	$R < \frac{2L}{\sqrt{LC}}$	Complex conjugate pair	Underdamped

Table 2: Complete solution to the series RLC circuit

Figure 4 shows the response of the circuit in Figure 3 to a 1V step input for a circuit where ω_n is normalized to 1 rad/s. The figure shows two underdamped cases ($\alpha = 0.1$ and 0.707), one critically damped case (α=1), and one overdamped case (α=1.5). The least damped case clearly shows classic damped harmonic oscillation, where energy is being transferred between the inductor and the capacitor and slowly dissipated in the resistor, behavior identical to the damped harmonic motion of the spring-mass-damper system of Figure 2. The transfer of reactive power between the capacitor and inductor for the least damped case (α=0.1) is shown in

Figure 5. As the reactive power increases in the capacitor, it decreases in the inductor. When the reactive power is at a local maximum in the capacitor, it is at a local minimum in the inductor and vice-versa.

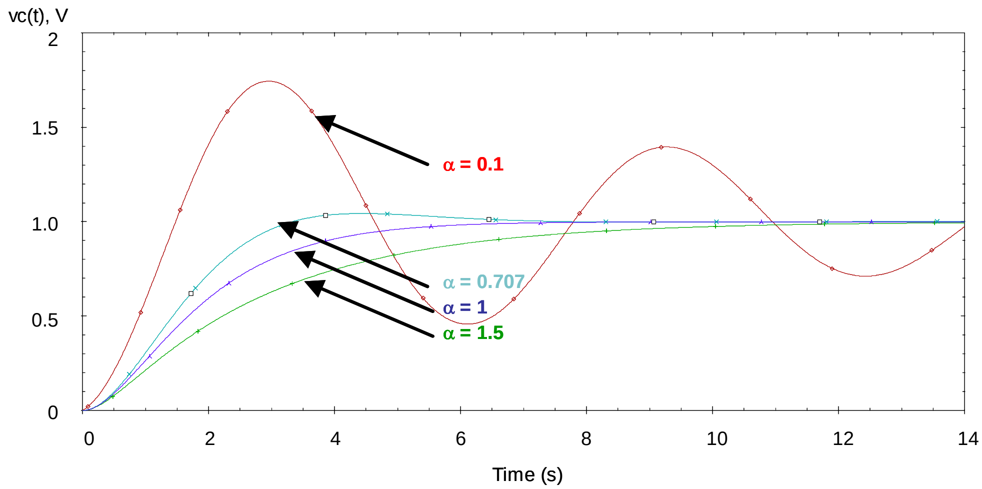

Figure 4: Response of the series RLC circuit to a 1V step input

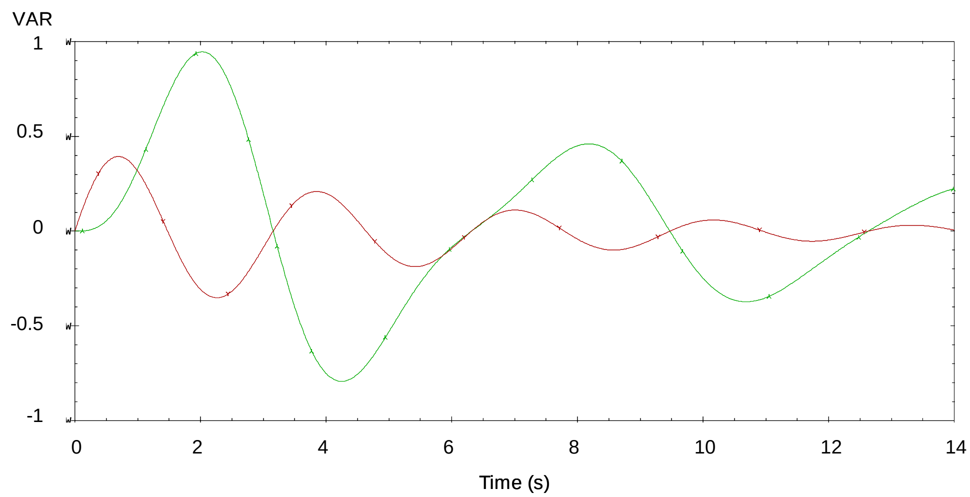

Figure 5: Reactive power transfer between capacitor (green) and inductor (red)

6.1.3 Signals and Systems.

The signals and systems course, EE381, has two global objectives. First, to teach the students the basic mathematical techniques necessary for describing, analyzing and designing LTI systems. Second, the course strives to develop the students' appreciation of the broad applicability of transform theory as a means for obtaining important insights into the nature of systems. The concept of a *signal* is used to describe the energy state of a natural phenomenon and provide information about its evolution in space and in time. The concept of a *system* describes the transformation of an input signal into an output signal.

Time Domain and Fourier Analysis. Initially, the students are introduced to two time domain techniques to describe the relationship between input and output signals based on the properties of an LTI system.

First, the LTI system is characterized by its impulse response, h(t) or h[n], and the output signal is determined by the convolution of an input signal with the impulse response, described in Figure 6. This is based on the principles that the impulse response completely characterizes the properties of a system, and that an arbitrary input can be represented as the weighted superposition of time-shifted impulses.

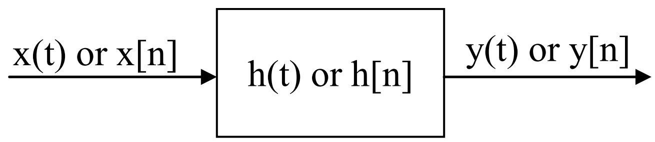

Figure 6. Characterization of an LTI system.

Another technique for characterizing a continuous-time LTI system is to relate the input and output signals by a linear, constant-coefficient differential equation. The corresponding description for a discrete-time system is through a linear, constant coefficient difference equation. The differential equation provides an implicit relationship between the input and output signals. To obtain a unique explicit description of the output signal, the differential equation must be solved for a particular input, *x(t)*, and initial conditions must be specified.

Using the second-order circuit in Figure 3, and letting $v(t) \sim x(t)$ and $v_c(t) \sim y(t)$, the differential equation describing the RLC circuit as a linear system is

$$LC\frac{d^2 y(t)}{dt^2} + RC\frac{dy(t)}{dt} + y(t) = x(t)\,. \tag{23}$$

The Fourier Transform of this differential equation is then,

$$[LC(j\omega)^2 + RC(j\omega) + 1]\,Y(j\omega) = X(j\omega) \tag{24}$$

so the *frequency response* of the system can be written as,

$$\mathrm{H}(j\omega) = \frac{\mathrm{Y}(j\omega)}{\mathrm{X}(j\omega)} = \frac{\omega_0^2}{(j\omega)^2 + 2\zeta\omega_n(j\omega) + \omega_0^2} \tag{25}$$

where $\omega_n = 1/\sqrt{LC}$ is the *undamped natural frequency* of the system (same as in equation (22)) and $\zeta = R\sqrt{LC}/2L$ is the *damping ratio* of the system. This dimensionless damping ratio corresponds to the damping factor, α, in Equation (22), by the relation, $\alpha = \zeta\omega_0$.

The magnitude of the complex $H(j\omega)$ provides a *frequency domain* perspective on the second-order circuit, which complements the step-response *time domain* perspective from the circuits course. The logarithmic value of $|H(j\omega)|$ is plotted against the frequency (normalized by ω_0) in Figure 7 for four different values of the damping ratio. These plots, considered along with the step response plots in Figure 4, provide crucial information about trade-offs between time and frequency domain performance characteristics for circuits (systems) of a given order. Some of these include:

— the greater the damping ratio, the smaller the frequency selectivity of the circuit for the same undamped natural frequency. If we define the *cutoff frequency* as the frequency at which 20log|H(jω)|=-3dB, then larger values of damping ratios correspond to lower cut-off frequencies of the passband; a steeper rise time in the time domain corresponds to a higher cutoff frequency in the frequency domain.

— the minimum ξ to prevent overshoot in the time domain ($\xi = 1$) is different than the minimum ξ that has no overshoot in the frequency domain ($\xi = \sqrt{2}/2 \approx 0.707$); the first value corresponds to a Bessel frequency response (minimum overshoot) characteristic, while the second corresponds to a Butterworth frequency response (maximally flat passband) characteristic.

— there is a minimum time period, or rise time, over which it is possible to change between two energy states, a generic "0" and "1", for a given natural frequency. This suggests a minimum time-bandwidth product, which corresponds to the uncertainty principle upon which quantum mechanics is based.

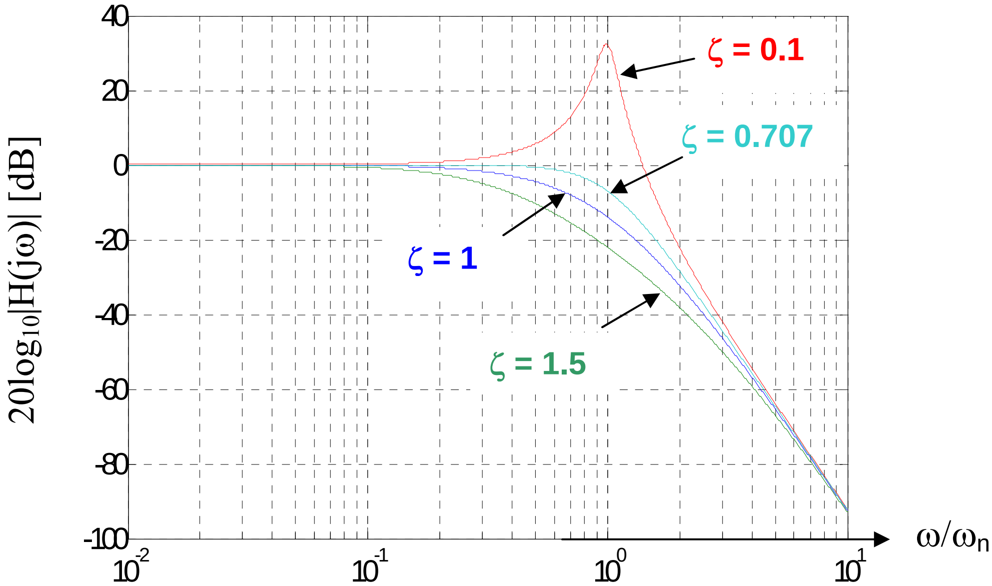

Figure 7. Frequency response versus normalized frequency for a second-order system.

Laplace Analysis. Another transform theory that is addressed in the signals and systems course is the Laplace transform. Since the mechanics of determining the Laplace transform were covered in MA364, the signals and systems course is focused on using the transform to characterize a system. A system's stability characteristics, for example, derive from the locations of the roots of the denominator of the system transfer function, also called the poles of the transfer function. In order for a causal system to be stable, the poles must be located in the negative real half-plane (left of the $j\omega$-axis). For a second-order system, the pole locations depend on the natural frequency and damping coefficient, shown in Figure 8. When $\xi = 1$, the repeated poles lie on the negative real axis, at a distance of ω_n from the imaginary axis. For $\xi > 1$, the repeated poles split, with one moving toward the imaginary axis and the other moving away from it. Both poles remain on the negative real axis. Finally, for $\xi < 1$, the poles split and form a conjugate pair along the $\omega = \omega_n$ circle, moving closer to the $j\omega$-axis as the damping coefficient decreases. The passive second-order circuit becomes marginally stable when $\zeta \to 0$, and the poles move onto the $j\omega$-axis. This occurs for an undamped circuit, when $R = 0$, and the circuit resonates at the natural frequency. This forms the basis for oscillator design in future electronic circuits courses.

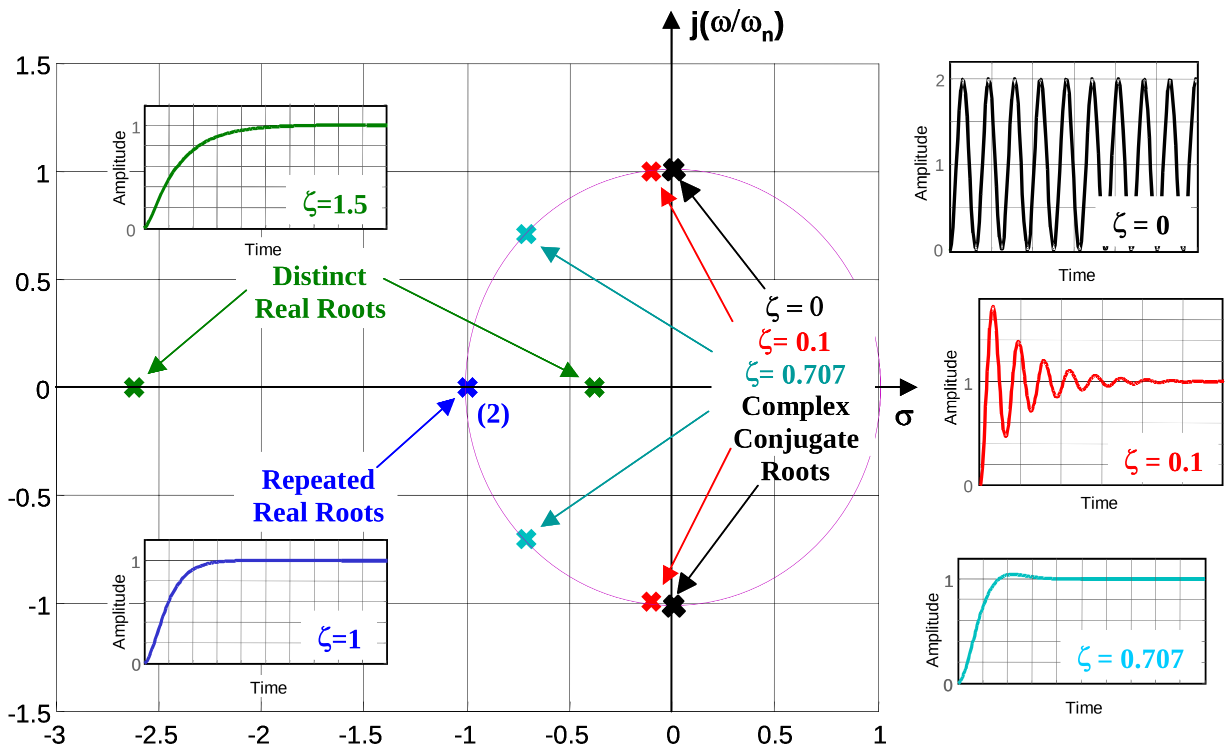

Figure 8. S-plane plot of pole-zero diagrams for five damping coefficient values. Inset plots are time-domain step responses corresponding to the five damping coefficients.

The signals and systems course provides the electrical engineering students with additional insight into the time and frequency domain properties of generic second-order systems. Using the previously introduced second-order circuit and corresponding differential equation, these "new" concepts are explained in the context of the damped harmonic oscillator and energy transfer among two storage elements.

6.1.4 Electromagnetic Fields.

The electromagnetic fields course, EE383, focuses on the formulation of Maxwell's Equations from experimental laws, and examines solutions to the wave equation for time-harmonic fields in unbounded media as well as in transmission lines and waveguides.

The propagation of electromagnetic fields in a lossy medium or along a lossy transmission line can be modeled by a network of lumped parameter circuit elements such that the per-unit-length power attenuation and phase-shift between the electric and magnetic field components can be described by a second-order differential equation.

Figure 9 shows a model of a lossy parallel-plate transmission line of differential length, Δz. In the general case, the losses in the transmission line derive from the non-zero resistance of the conductors and the non-infinite resistance of the dielectric medium.

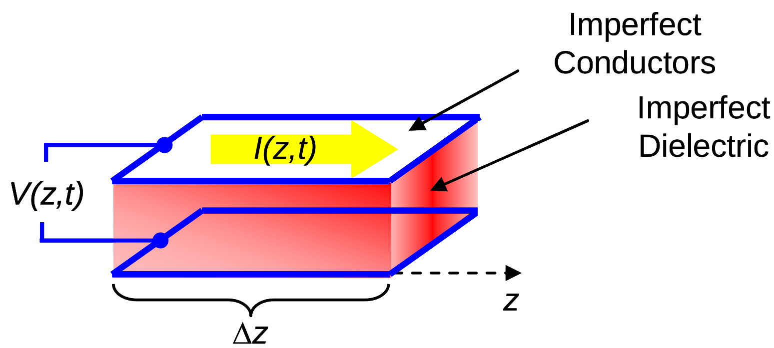

Figure 9. Diagram of a transmission line.

If the plates are assumed to be of infinite extent, allowing us to ignore fringing field effects, then the current-voltage characteristics of the differential length of the transmission line can be represented by the lumped-parameter circuit model in Figure 10.

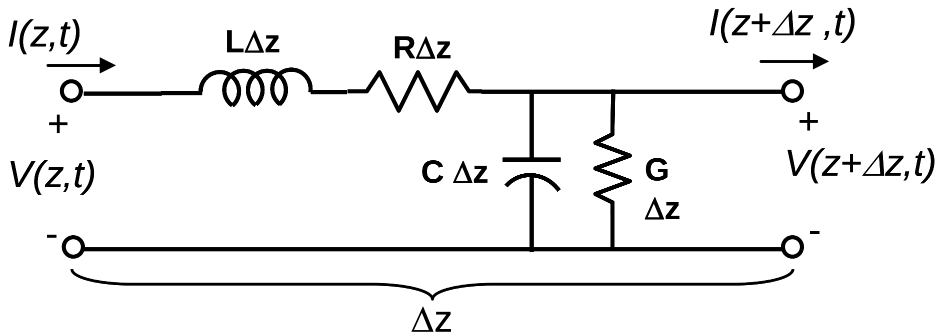

Figure 10. Lumped-parameter circuit model of a transmission line.

Here, **L** and **C** are the per-unit-length inductance and capacitance of the transmission line, and depend on the geometry of the transmission line and the material properties of the dielectric. **R** and **G** represent the non-zero, per-unit-length series resistance of the conductor plates and shunt conductance of the dielectric, respectively. The relationship between the current and voltage at the input and output terminals can be represented by the transmission line equations,

$$\frac{\partial V(z,t)}{\partial z} = -(R + \mathrm{L}\frac{\partial}{\partial t})I(z,t)$$
$$\frac{\partial I(z,t)}{\partial z} = -(G + \mathrm{C}\frac{\partial}{\partial t})V(z,t) \tag{26}$$

These equations describe the energy transfer between the magnetic field induced by current flowing along the plates of the transmission line and the electric field induced across the dielectric separating the free charges on the two conducting plates. Assuming sinusoidal, steady-state conditions, the voltage and current can be expressed as phasors, $\underline{V}(z)$ and $\underline{I}(z)$, where

$V(z,t) = \Re e\{\underline{V}(z)e^{j\omega t}\}$ and $I(z,t) = \Re e\{\underline{I}(z)e^{j\omega t}\}$. The transmission line equations can then be rewritten as,

$$\frac{d\,\underline{V}(z)}{dz} = -(R + j\omega\mathrm{L})\,\underline{I}(z)$$
$$\frac{d\,\underline{I}(z)}{dz} = -(G + j\omega\mathrm{C})\,\underline{V}(z) \qquad (27)$$

and, taking the second derivative of the first equation, the two equations can be uncoupled, with the resulting second-order differential equation for the voltage as a function of position along the transmission line,

$$\frac{d^2\,\underline{V}(z)}{dz^2} = (R + j\omega\mathrm{L})(G + j\omega\mathrm{C})\,\underline{V}(z)$$
$$= \bar{\gamma}^{\,2}\,\underline{\mathrm{V}}(\mathrm{z}) \qquad (28)$$

where $\bar{\gamma} = \sqrt{(\mathrm{R} + \mathrm{j}\omega L)(\mathrm{G} + \mathrm{j}\omega C)} = \alpha + j\beta$ is the complex propagation constant. The real part of the propagation constant, α, is the *attenuation constant* of the transmission line, which represents all energy loss with distance along the direction of propagation. The imaginary part, β, is the *phase constant*, which represents the phase evolution of the signal with distance along the direction of propagation. Alternatively, we can define the *wavelength* of the signal within the medium as $\lambda = 2\pi/\beta$, which describes the distance over which the signal phase has evolved by 2π radians. The general solution to the second-order differential equation for $\underline{V}(z)$ is

$$\underline{V}(z) = \bar{V}^{+}e^{-\bar{\gamma}z} + \bar{V}^{-}e^{\bar{\gamma}z}$$
$$= \bar{V}^{+}e^{-\alpha z}e^{-j\beta z} + \bar{V}^{-}e^{\alpha z}e^{j\beta z} \qquad (29)$$

where $\bar{V}^{+}$ and $\bar{V}^{-}$ are complex amplitudes of the forward and backward propagating components of the voltage signal, whose values are determined by the boundary conditions of the transmission line. If the coupled first-order differential equations are solved for the current, the current signal can be written as

$$\underline{I}\,(\mathrm{z}) = \frac{1}{\bar{Z}_0}\left(\bar{V}^{+}e^{-\bar{\gamma}z} - \bar{V}^{-}e^{\bar{\gamma}z}\right), \qquad (30)$$

where $\bar{Z}_0 = \sqrt{\dfrac{R + j\omega L}{G + j\omega C}} = \left|\bar{Z}_0\right|e^{j\phi_z}$ is the *complex characteristic impedance* of the transmission line. $\left|\bar{Z}_0\right|$ represents the amplitude ratio between the voltage and current at every point along the transmission line, and ϕ_z indicates the phase shift between the two values.

To obtain a simplified picture of the evolution of the voltage and current signals, assume that the transmission line is infinitely long (or that the load impedance is perfectly matched with the characteristic impedance), so there is no reflection by the load $(\bar{V}^{-} = 0)$. Then, assuming that there was no initial phase at z = 0 or that $\bar{V}^{+}$ is purely real, the propagating voltage and current signals can be written as

$$V(z,t) = \bar{V}^{+}e^{-\alpha z}\cos(\omega t - \beta z) \quad \text{and} \quad I(z,t) = \frac{\bar{V}^{+}}{\left|Z_0\right|}e^{-\alpha z}\cos(\omega t - \beta z - \phi_z). \qquad (31)$$

Figure 11 shows a snapshot in time ($t = 0$) of the voltage and current signals as a function of distance along the transmission line, normalized by the wavelength of the signal inside the transmission line. The behavior is analogous to the time domain behavior of the underdamped second-order RLC circuit presented in the introductory circuits course. The transmission line demonstrates underdamped behavior because the loss elements (**R** and **G**) are generally very small. In the circuits example, the rate of energy transfer between capacitor and inductor corresponded to the natural frequency of the circuit (radians per second), and the rate of energy dissipation (per second) corresponded to the decay rate. In the lossy transmission line, the rate of energy flow in the direction of propagation corresponds to the phase constant, β, of the transmission line (radians per meter), and the rate of energy dissipation (per meter) corresponds to the attenuation constant, α. The phase velocity of the signal along the transmission line unifies the time and distance rates. An alternative insight is obtained by considering that the rates of energy transfer between capacitance and inductance per unit length of the transmission line are related the speed at which the signal propagates along the line.

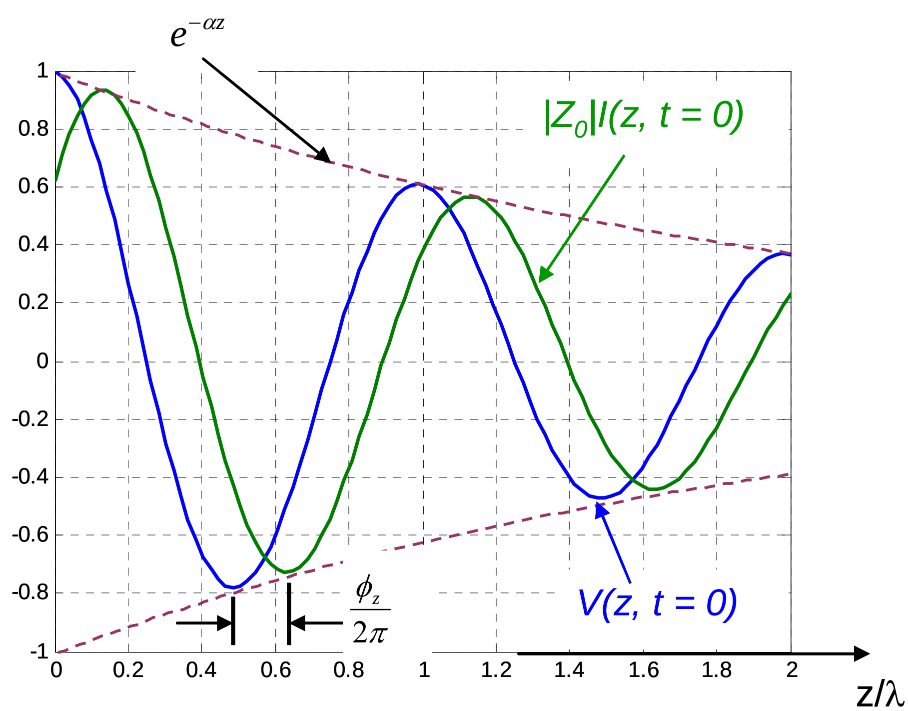

Figure 11. Voltage and current signals as a function of distance along transmission line at time t=0.

By taking advantage of the previous treatment of second-order systems, the new concept of electromagnetic field propagation along a transmission line is introduced in EE383 as a variation of the familiar behavior of the damped harmonic oscillator or RLC circuit. The characteristic damped oscillatory behavior, now a function of distance rather than of time, reflects the energy transfer between electric and magnetic energy storage elements with some loss along the direction of propagation of the signal.

6.1.5 Advanced Circuit Analysis.

In our advanced circuits course, EE462, students learn about filters and oscillators, fundamental components of communications circuits. In these circuits, a node voltage or branch current represents information rather than just energy. Still, one can approach these circuits from a perspective of energy transfer. The objective with filters is to transfer energy at unwanted frequencies through the loss element so as to attenuate it, but pass the energy at desired frequencies. With filters, the response of interest is usually the frequency response, rather than the time domain response, whereas with oscillators, the time domain behavior is the response of interest.

Second-Order Filters. A series RLC circuit such as Figure 3 can be used as a second-order low-pass filter if the output is taken as the voltage across the capacitor. In EE462, we derive the transfer function of the filter using phasor analysis. In phasor analysis, we use the same KVL analysis as in EE302, but this time use the complex impedance of the components rather than the inductance, capacitance, and resistance. This analysis is only valid for steady-state conditions, but that assumption is adequate for the filter designs we consider in this course. Using phasor analysis, the KVL equation corresponding to Equation (12) is

$$\underline{Z}_L \underline{I} + R\underline{I} + \underline{Z}_C \underline{I} = \underline{V}, \tag{32}$$

where

$$\underline{Z}_L = j\omega L, \tag{33}$$

and

$$\underline{Z}_C = \frac{1}{j\omega C}. \tag{34}$$

Therefore

$$j\omega L\underline{I} + R\underline{I} + \frac{1}{j\omega C}\underline{I} = \underline{V}. \tag{35}$$

We can solve for the current,

$$\underline{I} = \frac{\underline{V}}{j\omega L + R + \frac{1}{j\omega C}} = \frac{\underline{V}(j\omega C)/LC}{(j\omega)^2 + j\omega\frac{R}{L} + \frac{1}{LC}}. \tag{36}$$

Since the output voltage is $\underline{Z}_C \underline{I}$, the transfer function becomes

$$H(j\omega) = \frac{\underline{V}_{out}}{\underline{V}} = \frac{\underline{Z}_C \underline{I}}{\underline{V}} = \frac{1/LC}{(j\omega)^2 + j\omega\frac{R}{L} + \frac{1}{LC}} = \frac{\omega_n^2}{(j\omega)^2 + 2\zeta\omega_n(j\omega) + \omega_n^2}, \tag{37}$$

which is the same as Equation (25). As we showed in Section 6.1.3, a filter with a maximally flat passband (Butterworth filter) has a damping factor of 0.707. The frequency response of a series RLC circuit with parameters chosen to be a Butterworth filter is shown in Figure 12.

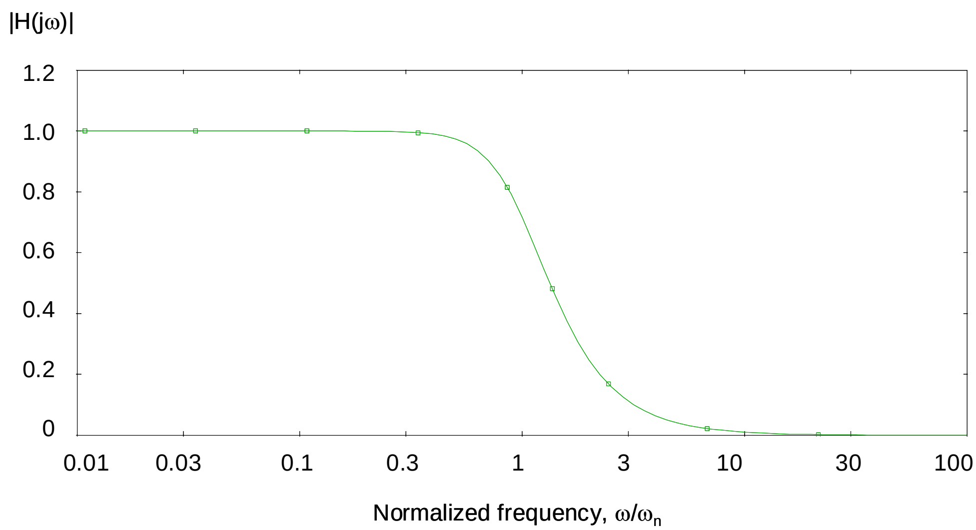

Figure 12. Second-order Butterworth low-pass filter frequency response.

Oscillators. A basic model of an oscillator consists of an amplifier and a frequency-selective network connected in a positive-feedback loop, shown in Figure 13.

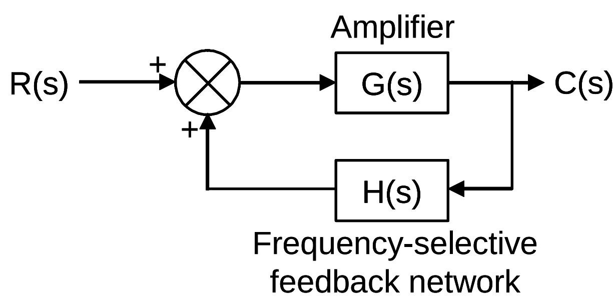

Figure 13. Basic model of an oscillator.

The transfer function of this system is

$$T(s) = \frac{C(s)}{R(s)} = \frac{G(s)}{1 - G(s)H(s)}. \tag{38}$$

In order for this system to oscillate, it must satisfy the Barkhausen criterion, $-G(s)H(s) = -1$.

One oscillator that can be modeled as a second-order system is the Wien-bridge oscillator, shown in Figure 14. This circuit has two energy storage elements so the student should immediately recognize that this circuit can be modeled with a second-order differential equation. The student should also recognize that since we are attempting to design an oscillator, the R and C parameters will be chosen to create a system with poles on the $j\omega$-axis so as to introduce harmonic oscillation, as shown in Figure 8.

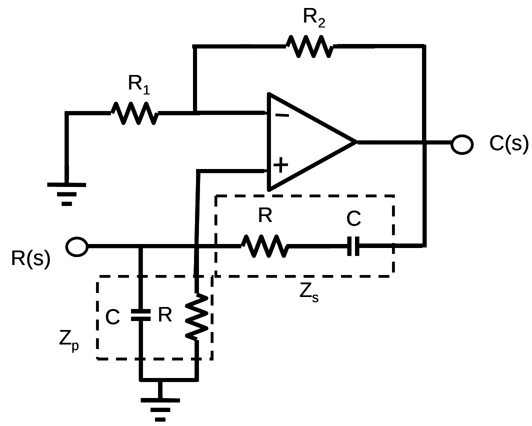

Figure 14: Wien-bridge oscillator.

The amplifier part of the circuit is an OPAMP connected in a non-inverting configuration which has a gain of $G(s) = 1 + R_2 / R_1$. The frequency-selective feedback network consists of two RC circuits in a voltage-divider configuration, $H(s) = Z_P /(Z_S + Z_P)$, where

$$Z_P = \frac{R}{1 + sRC} \text{ and } Z_S = R + \frac{1}{sC}. \tag{39}$$

The denominator of the transfer function is therefore

$$1 - G(s)H(s) = 1 - \left(1 + \frac{R_2}{R_1}\right)\left(\frac{Z_P}{Z_S + Z_P}\right) = 1 - \frac{1 + R_2 / R_1}{3 + sRC + 1/sRC}. \tag{40}$$

To satisfy the Barkhausen criterion, the phase shift of G(s)H(s) must be zero, which occurs when $sRC = 1/sRC$ or substituting $s = j\omega$, when $\omega_o RC = 1/\omega_o RC$ or $\omega_o = 1/RC$. When the phase shift is zero, the magnitude of *G(s)H(s)* must equal 1, or $\frac{1}{3}\left[1 + \frac{R_2}{R_1}\right] = 1$. Therefore $\frac{R_2}{R_1} = 2$ for the circuit to oscillate.

When the Barkhausen criterion is exactly satisfied, the poles of the transfer function are located on the $j\omega$-axis in the *s*-plane. In practice, it is necessary to make the gain slightly larger than 2, pushing the poles slightly to the right, otherwise the circuit may not oscillate, due to unmodeled parasitic resistance that would have moved the poles slightly to the left of the $j\omega$-axis. A practical oscillator that has poles slightly to the right of the $j\omega$-axis also includes a limiter circuit (not shown in Figure 14) to prevent the oscillations from growing without bound. The output from a Wien-bridge oscillator with a limiter is shown in Figure 15. This is an example of undamped harmonic oscillation. Figure 15 is analogous to Figure 4 with a damping factor of $\alpha = 0$ and Figure 8 with $\zeta=0$.

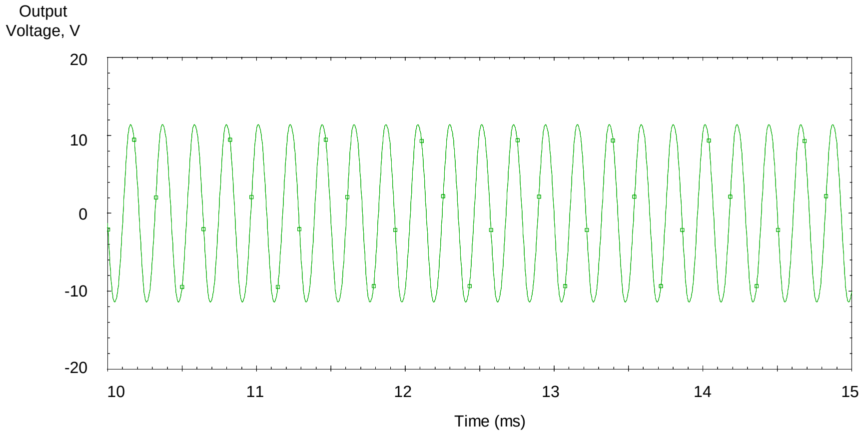

Figure 15: Wien-bridge oscillator output

6.1.6 Solid State Electronics.

Even digital logic circuits exhibit effects that can be modeled by second-order systems. In EE486, Solid State Electronics, students are introduced to a MOSFET inverter, such as the one in Figure 16.

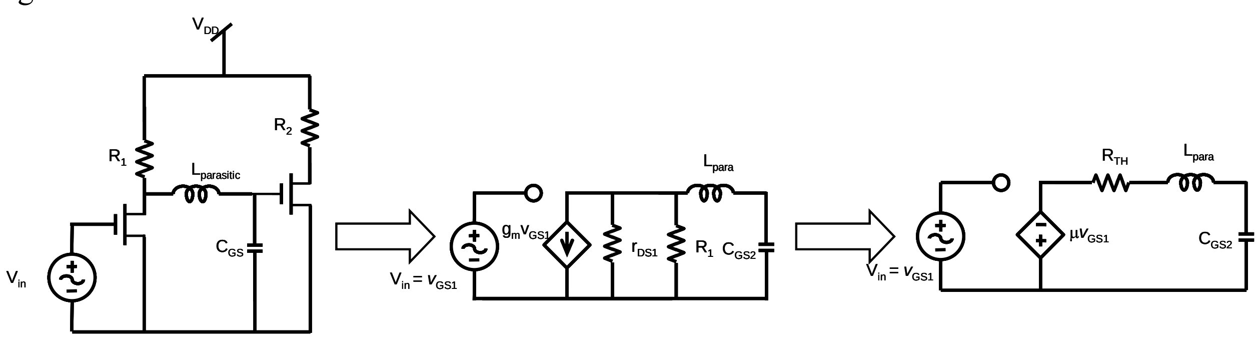

Figure 16. MOSFET Inverter circuit.

While analyzing the transient behavior of one MOSFET inverter driving another, using the small signal model of the first MOSFET, Q1, and including parasitic inductance in the circuit and the gate-to-source capacitance of the second MOSFET, we again have a circuit with two energy storage elements. The middle part of Figure 16 is not immediately recognizable as series RLC circuit. However, performing a Norton-to-Thevenin source transformation of the dependent current source, r_{DS1} and R_1, produces the series RLC circuit on the right, where R_{TH} is the parallel combination of R_1 and r_{DS1}. If we set R_1 to be too large, then the response at the gate of Q2 to a pulse is shown in Figure 17. The second-order system is over damped and the inverter introduces a relatively large delay. If the transistor and circuit board are fixed, the only easily adjusted parameter is R_1. If we reduce R_1, the response will speed up. However, reducing R_1 too much produces an under damped response, shown in Figure 18. This circuit exhibits the behavior known as gate ringing. Figure 18 is yet another example of the classic damped harmonic oscillation, similar to Figures 2, 4, and 11.

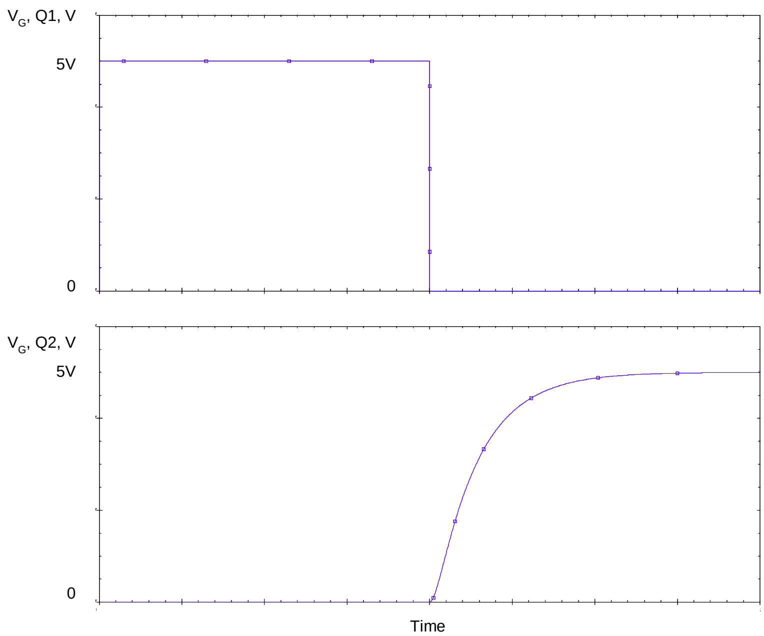

Figure 17: MOSFET Inverter step response, overdamped.

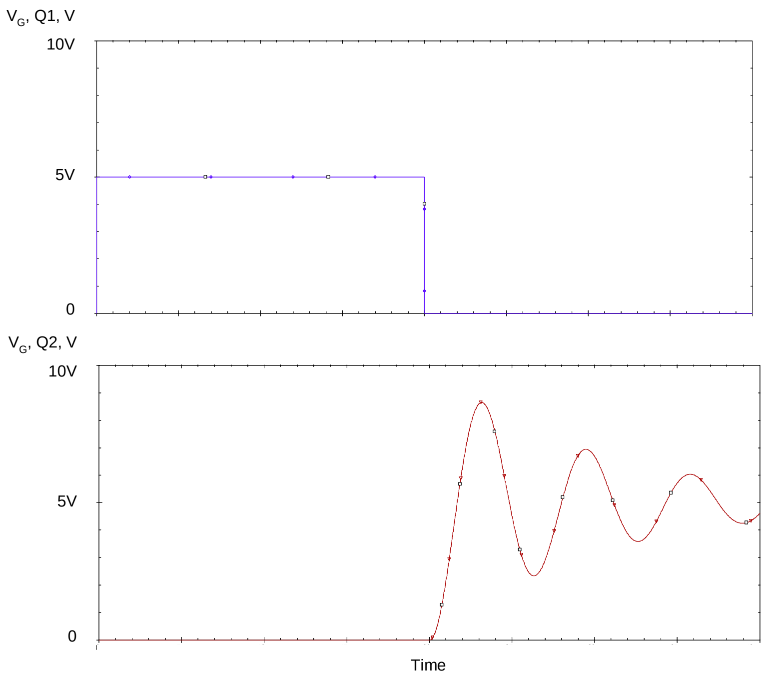

Figure 18: MOSFET inverter step response, underdamped showing gate ringing.

6.2 Electrical Engineering Elective Courses.

6.2.1 Photonics Engineering.

The photonics engineering course, EE483, addresses the theory and operating principles of various optoelectronic devices, including lasers. One of the principles of laser theory is the resonant extraction of energy from the gain medium by the electromagnetic field that circulates in the laser cavity. The extraction of energy depends on population inversion of the gain medium as well as the characteristic frequency response of the gain material, which is characterized by the lineshape function. Although the complete transient response is beyond the scope of the course, the steady state analysis is a straightforward application of the damped harmonic oscillator model to electron dipole transitions to derive the lineshape function.

If we model the restoring force between a nucleus and an electron as a simple spring, and the instantaneous displacement is *x(t)*, then the system description is analogous to the spring-mass-damper problem, with the damping effect accounting for (at least) the energy decay of a harmonically moving electron that is coupled into a radiated electromagnetic field. This analogy is shown in Figure 19.

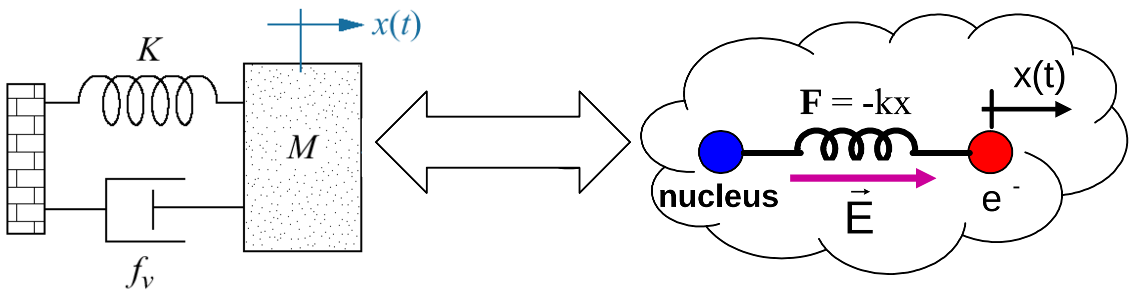

Figure 19. Analogy between mechanical and photonic systems.

By Newton's Second Law,

$$m\frac{d^2x(t)}{dt^2} = -kx(t) - eE_x(t) \qquad \text{or} \qquad \frac{d^2x(t)}{dt^2} + \omega_0^2 x(t) = -\frac{e}{m}E_x(t) \qquad (41)$$

where $\omega_0 = \sqrt{k/m_e}$ is the resonance frequency of the electron system, k models the bonding force between the nucleus and electron, m_e is the mass of the electron, and e is the electron charge. E_x is the component of the electric field in the x-direction. Introducing the damping effect into the equation of motion yields

$$\frac{d^2x(t)}{dt^2} + \gamma\frac{dx(t)}{dt} + \omega_0^2 x(t) = -\frac{e}{m_e}E_x(t), \qquad (42)$$

where γ is the damping coefficient that accounts for energy dissipation through radiative processes (spontaneous emission) and non-radiative processes (phonon scattering, collisions).

Assuming a sinusoidal driving field and a sinusoidal response of the electron displacement, we obtain the frequency response of the electron system by taking the Fourier Transform,

$$\frac{X(j\omega)}{E(j\omega)} = \frac{-e/m_e}{(j\omega)^2 + \gamma(j\omega) + \omega_0^2} . \tag{43}$$

The dipole moment of an individual atom can be written as $\mu = -ex(t)$, where $x(t)$ is the displacement of the oppositely signed charges from equilibrium. The macroscopic polarization is, then, the density of dipole moments per unit volume, or $P = N\mu = -Nex(t)$, where N is the dipole density. Assuming sinusoidal displacement, the equivalent relation in the frequency domain is $P(j\omega) = -NeX(j\omega)$.

The polarization of a material induced by an electric field is described by the constitutive relation

$$P(j\omega) = \varepsilon_0 \chi(j\omega) E(j\omega) \tag{44}$$

which assumes that the field intensity is low enough to insure linearity and that the material is isotropic. $\chi(\omega)$ is the susceptibility of the medium, ε_0 is the free space permittivity, and E is the electric field inducing the polarization. The relation is written in the frequency domain to avoid unnecessary complexity of convolution with a non-instantaneous atomic system response. Combining the three equations of a simplified model of microscopic behavior and the macroscopic constitutive relations yields the complex susceptibility,

$$\chi(j\omega) = \frac{P(j\omega)}{\varepsilon_0 E(j\omega)} = \frac{-NeX(j\omega)}{\varepsilon_0 E(j\omega)} = \frac{Ne^2/\varepsilon_0 m_e}{(\omega_0^2 - \omega^2) + j\gamma\omega}, \tag{45}$$

which can be rewritten as a sum of a real and imaginary component, $\chi(j\omega) = \chi' + j\chi''$. Each component can be related to a physical property of the optical medium. The refractive index of the medium, *n*, is defined as,

$$n = 1 + \frac{\chi'}{2} = \frac{Ne^2}{\varepsilon_0 m_e} \frac{(\omega_0^2 - \omega^2)}{(\omega_0^2 - \omega^2)^2 + (\gamma\omega)^2}, \tag{46}$$

which describes the factor that modifies the propagation constant in the medium of an electromagnetic field at a particular frequency, ω. The absorption constant of the medium, α, is defined as,

$$\alpha = -\frac{\pi}{\lambda}\chi'' = \frac{\pi N e^2}{\lambda \varepsilon_0 m_e} \frac{\gamma\omega}{(\omega_0^2 - \omega^2)^2 + (\gamma\omega)^2} . \tag{47}$$

This absorption constant is the same as in the model for the transmission line, following Equation (28), except that we now explicitly derive its frequency dependence. By assuming that $\gamma << \omega_0$, the imaginary part of the susceptibility can be rewritten as,

$$\chi'' \cong -\underbrace{\frac{Ne^2}{\varepsilon_0 m_e}\frac{1}{\gamma\omega_0}}_{\chi_0''} \underbrace{\frac{1}{1 + [2(\omega - \omega_0)/\gamma]^2}}_{\delta\omega} . \tag{48}$$

The normalized imaginary susceptibility plot in Figure 20 shows that the functional shape of the absorption constant is Lorentzian. The lineshape of a laser transition, which describes the spectral characteristics of a laser gain medium, is written in terms of the absorption constant as,

$$\sigma(\omega) = \frac{2\alpha(\omega)}{N}, \tag{49}$$

where N is the atomic density. Experimentally, the lineshape of a laser transition is Lorentzian, as predicted by the simple electron dipole transition model shown in Figure 19.

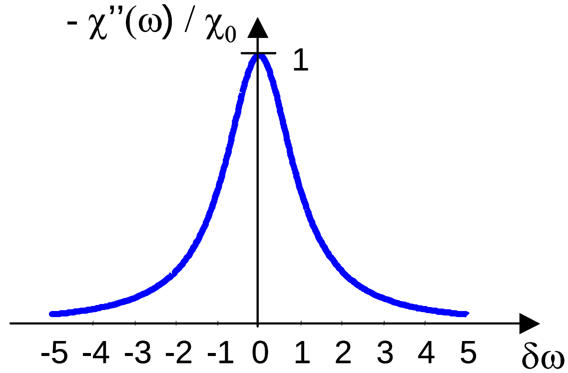

Figure 20. Normalized imaginary part of complex susceptibility vs frequency deviation from the resonant frequency of atom-electron system.

By using the damped harmonic oscillator model to describe the interaction between a nucleus and electron, we are able to derive the characteristic spectrum corresponding to a general atomic gain medium. All insights previously obtained in the analysis of second-order systems and damped harmonic oscillators can be brought to bear in helping understand this relatively complex process of energy transfer between the gain medium and the electromagnetic field that propagates through it. Under appropriate thermodynamic conditions, the attenuation constant derived here becomes the gain constant of the medium, explaining laser action.

6.2.2 Control Systems.

At West Point, there is a single controls course that is jointly taught by Electrical Engineering and Mechanical Engineering faculty members. In XE472, Dynamic Modelling and Control, the students revisit mechanical, electrical, and electromechanical systems to better understand stability and design control systems to modify the natural behavior of physical systems. In this course, the students revisit the RLC circuit and the spring-mass-damper mechanical system from the perspective of the Laplace transform and control theory.

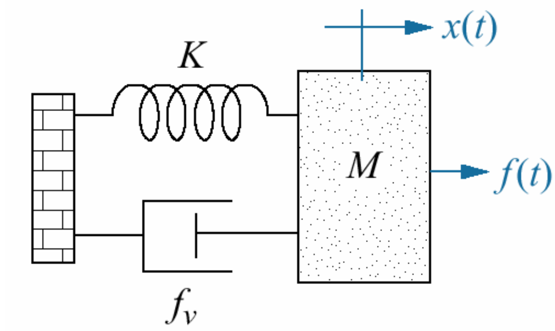

Figure 21. Forced spring, mass, damper problem.

Similar to the approach previously developed in physics, the equation of motion for this mechanical system with an external forcing function is

$$M\frac{d^2x(t)}{dt^2}+f_v\frac{dx(t)}{dt}+Kx(t)=f(t). \tag{50}$$

The Laplace transform is used to simplify the analysis of this second-order differential equation

$$Ms^2X(s)+f_vX(s)s+KX(s)=F(s), \tag{51}$$

resulting in the following form

$$\left(Ms^2+f_vs+K\right)X(s)=F(s) \quad\Rightarrow\quad G(s)=\frac{X(s)}{F(s)}=\frac{1}{Ms^2+f_vs+K}. \tag{52}$$

The stability of this system is then described by considering the pole locations in the s-plane and determining whether the poles lie in the right-half-plane or left-half-plane. The system characteristics follow directly from the poles of the system – the characteristic equation, which was introduced in differential calculus.

Similarly, the analysis of the inverting operational amplified is revisited using Laplace transform techniques, this time using two capacitors as the energy storage devices, as shown in Figure 22.

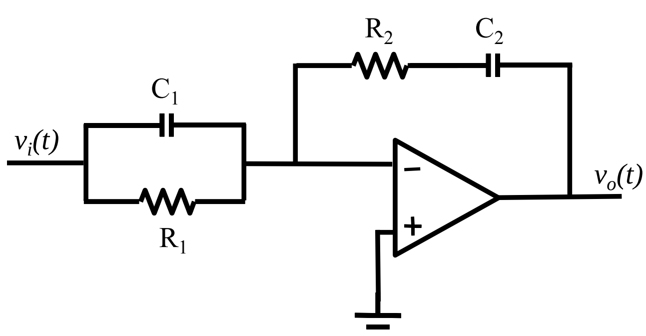

Figure 22. Inverting operational amplifier circuit.

Here the equation governing the transfer function is

$$\frac{V_o(s)}{V_i(s)}=-\frac{Z_2(s)}{Z_1(s)},\text{ with } Z_1(s)=\frac{1}{C_1s+1/R_1}\text{ and } Z_2(s)=R_2+\frac{1}{C_2s}, \tag{53}$$

resulting in

$$G(s) = -\frac{Z_2(s)}{Z_1(s)} = -\left[\left(\frac{R_2}{R_1} + \frac{C_1}{C_2}\right) + R_2C_1s + \frac{1/R_1C_2}{s}\right] = -\left[R_2C_1s^2 + \left(\frac{R_2}{R_1} + \frac{C_1}{C_2}\right)s + \frac{1}{R_1C_2}\right] \quad (54)$$

In the Dynamic Modeling and Control course, this results in the active circuit representation of a proportional-plus-integral-plus-derivative (PID) compensator or controller.

In this course, knowledge of second-order systems is used to design and control other systems in order to obtain specific transient and steady-state performance specifications.

7.0 Curriculum Integration Process.

In addition to developing specific topical linkages and recurring thematic examples, deliberate curriculum integration requires an institutional process to effectively implement. At West Point, the Electrical Engineering Program has adopted an approach that includes faculty classroom visitation, course proposal and evaluation, administrative oversight, brown bag lunches, web-based resources, and student participation

As part of the faculty evaluation process, each Electrical Engineering faculty member is required to maintain a Teaching Portfolio that requires each faculty member to visit at least one colleague's classroom each semester. While the primary purpose of these classroom visitations is to observe different teaching styles and provide a dialog focused on teaching, it also provides a mechanism through which faculty members can personally witness topical coverage in related courses.

At the end of each semester, course directors are required to assess the courses they taught and document successes and recommendations for change. At the beginning of each semester, course directors are required to review the course evaluation from the previous semester and develop a course proposal that describes the conduct of the course for the current semester. As part of the course proposal process, each course director is required to review the course evaluations for those courses that are linked to their course, through topical coverage and prerequisite structure.

Within the Electrical Engineering Program, an intermediate level of curricular oversight is provided by individual faculty who serve as Thread Directors. The Electrical Engineering Program is divided into six threads: (1) Electronics, (2) Circuits, (3) Digital Logic and Computer Architecture, (4) Design, (5) Communications and Photonics, and (6) Control and Power. The courses within each thread represent a natural topical thread. Each of the Thread Directors has the responsibility to routinely visit courses within their thread and meet each semester with Course Directors and the Program Director as part of the Course Proposal and Review process. This intermediate level of curricular oversight provides another natural institutional mechanism to reinforce deliberate curricular integration.

The brown bag lunches focus on discussions related to effective teaching techniques and include deliberate curriculum integration. While the brown bag lunches are intended to provide an informal forum to discuss teaching techniques and educational pedagogy, they also provide a forum to discuss topical linkages and recurring thematic examples.

Additionally, web-based resources are provided to support the dissemination of specific topical linkages and recurring thematic examples. Specifically, the main topical coverage of each course in the electrical engineering curriculum is identified in a course matrix cross-walk and foundational thematic examples like energy transfer, second-order differential equations, and the damped harmonic oscillator covered in this paper are archived.

Finally and perhaps most importantly, we actively engage students in this educational process. Each semester, the Electrical Engineering Program Director meets with each of the Electrical Engineering classes. These sessions usually take the form of an overview presentation to discuss recent activities in the Electrical Engineering Program and to solicit feedback from the students about the program. During these sessions, the students are made aware of the deliberate curriculum integration and reminded of their responsibility to retain knowledge and skills from previous courses in the curriculum. In this way, we enlist the participation of our students in their educational process.

8.0 Concluding Remarks.

This paper describes the importance of deliberate curriculum integration to improve course-to-course disciplinary linkages and reinforce foundational concepts. One specific thematic example was used to demonstrate how deliberate curriculum integration can be implemented in a typical electrical engineering curriculum.

When one considers the broad discipline of electrical engineering, there are a number of other foundational concepts that are considered core competencies or immutable concepts. A careful study of the topical coverage of each course in the curriculum will identify where each foundational concept occurs thereby providing the framework to develop similar deliberate linkages. In addition to specific disciplinary knowledge, curriculum integration should also include social, political, economic, and professional and ethical issues that are important skills for engineers that must practice in a global environment.

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