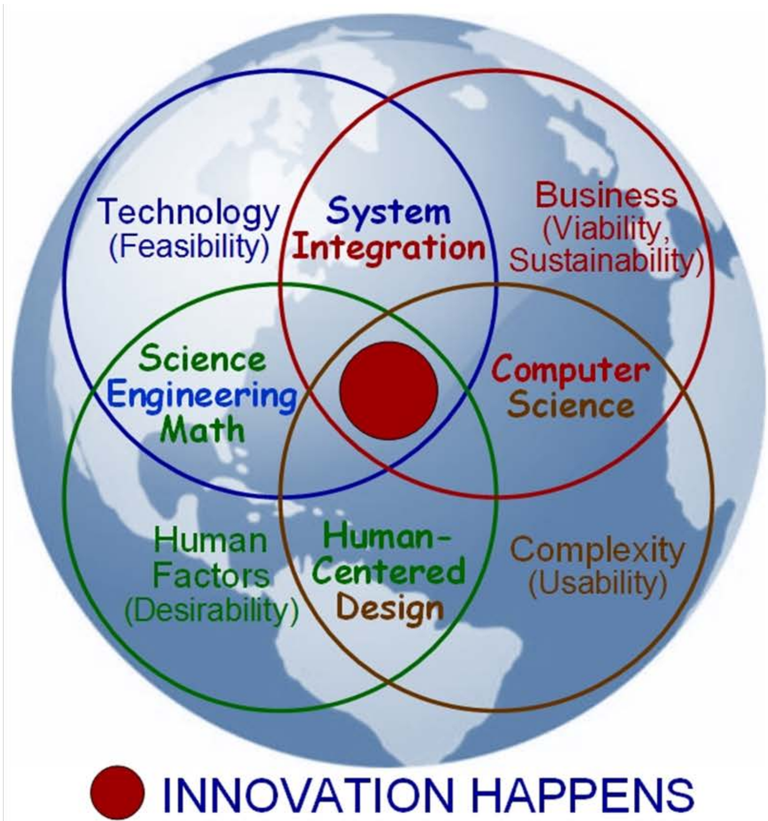
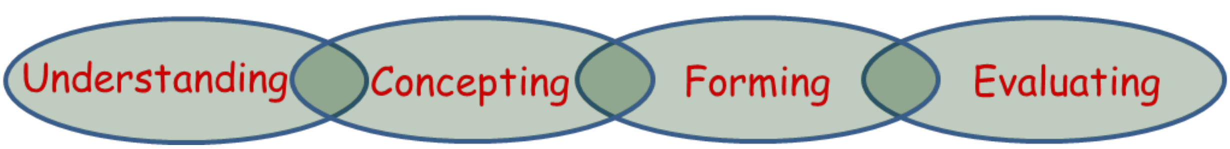
Innovation

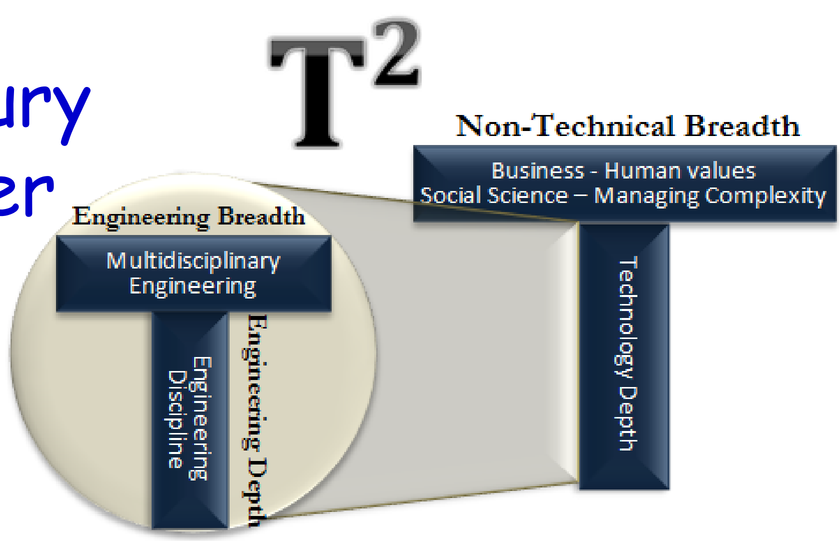
Innovation is Local.
You don't import it.
You don't export it.
You create it.
It is a way of thinking,
communicating,
and doing.



Human-Centered Design generates solutions to problems and opportunities driven by the needs, desires, and context of the people being designed for. It is a way of thinking, communicating, and doing every day.



21st - Century T² Engineer



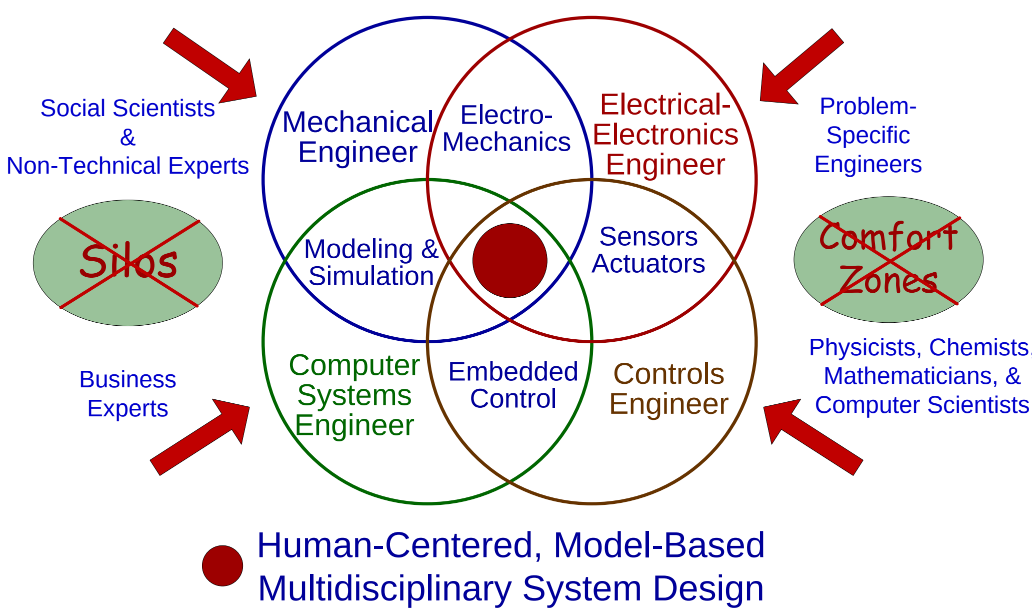
The Challenges Engineers Face

The problems the world faces are multidisciplinary, complex, and ever changing. Engineers, as the solvers of these problems, need to understand the impact of their solutions in a global context, emphasizing sustainability. Sustainability – the ability of one generation to meets its needs without compromising the ability of future generations to meet their needs – has three dimensions: economic, environmental, and social. Key tenets of sustainability include intelligent use of resources, improvement of the quality of life, and lessening the environmental impact. Innovative solutions require a new way of thinking, communicating, and doing; they must be human-centered, technologically feasible, commercially viable, usable from a complexity view, and sustainable in a global sense (top diagram).

Present-day engineering education requires a new engineering mindset. Multidisciplinary systems, like the environment, are complex and in a complex system, learning how all the pieces, constant and variable, interact gives a depth of understanding that averts catastrophe. Human-centered design, i.e., understanding the interfaces among technology, people, communities, governments, and nature, is what makes complexity manageable (middle diagram)

Clearly, the typical discipline-specific engineer is not well equipped to manage such complexity; not even an engineer with multidisciplinary engineering breadth can do an effective job. Complexity demands a skill set illustrated by the T^2 Engineer (bottom diagram): one with technology depth and also non-technical breadth, specifically human-centered design expertise capable of managing complexity.

As most of the challenges society faces are multidisciplinary, teams of T^2 engineers will be at the core of the multidisciplinary human-centered design team. Each of these T^2 engineers will have depth in mechanical, electrical, or computer systems engineering, and all will have knowledge in the design and implementation of computer-control systems. Communication is key, both among these individuals and with other experts, and modeling facilitates insight and communication. Modeling is the universal language for innovation. As the diagram below shows, comfort zones and silos must be avoided, as they are the greatest impediments to effective communication and innovation.



Signals, Systems, and Control

Wave to a friend and you are sending a signal; facial expressions transmit signals; our words form a signal. Turn on the radio, television, or computer – we are receiving signals (audio and video). Signals convey information. Signals can have many forms besides words and pictures. A signal can also be physical, e.g., when you throw a baseball, your arm is sending a signal to the ball "telling" it which way to go; the signal is a force that makes the ball accelerate. All signals must travel along channels, and all channels have limited capacity.

A system is different from a signal. A system usually involves two signals – an input and an output. A soda machine is a system: the input is money and the output is the can of soda. The money and soda can are signals. A person you are speaking to is a system: the input is your words and facial expressions and the output is the other person's words and facial expressions. A car is a system: the input signal is the force provided by the engine which makes the car move and the output is the speed of the car, measured by the speedometer. The baseball is a system: the input is the force you apply to the baseball in a particular direction and the output is the way the ball flies, including its speed and direction. Physical systems have devices to help them respond to inputs. An actuator is an input device (e.g., car engine) and a sensor is an output device (e.g., speedometer used for measurement).

An important property of a system is gain, which compares the size of the output signal to the size of the input signal. Consider a seesaw that is not centered – the gain of the system is greater than one, so it is an amplifier of distance. How is it a force amplifier? Can it amplify force and distance at the same time? Another important property of a system is phase shift, which compares the time shift of the input and output signals. A mother pushes her daughter on a swing and she only pushes when it is at its highest point. There is a time shift between the input and output. A system is linear if adding two inputs together gives an output that is the sum of the separate outputs. You can run a mile in 8 minutes with moderate effort. You try twice as hard and run a mile in 7.5 minutes. Is this a linear system? An employee gets paid time and a half for working on the weekend. Is this a linear system?

Control is used to improve the performance of a system. If the output of a system does not follow a desired command, then the error can be used to change the input so that the output is more desirable. This is feedback. In a servo system, the error between the desired motion and the actual motion is used to modify the input to make the error smaller. A car has cruise control. How is this a servo system? What is the command? What are the inputs and outputs in the feedback loop? A baseball player is trying to catch a fly ball. How is this a servo system? Another important use of feedback control is for stabilization. A broomstick standing on its end will fall over unless it is stabilized. When you balance a broomstick, how do you do it? What is the actuator? What is the sensor? Is more than one sensor involved? Is it harder to balance a short stick or a long stick? Why? Do humans need stabilization to stand up? Are you able to stand perfectly still? How much harder is it to stand still with your eyes closed? What sensors and actuators do you use to stand up? If you sit on a bicycle without moving, you fall over. But you don't fall over if you are moving forward. Why? Two people are talking on the phone, but the connection has a delay. Soon, they're talking over each other. Why is a delay bad for the stability of a feedback loop?

Signals, systems, and control provide a powerful basis for intellectual thought in science and technology.

<u>What Is An Engineering System and Why Do We Study Them?</u>

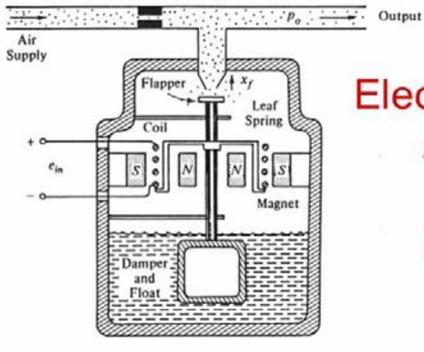
A system is an assemblage of components or elements intended to act together to accomplish an objective. Nothing in nature can be completely isolated from everything else, so we see that our selection of the boundaries of the system depends on the purpose and limitations of our study. Almost everything can be considered a system at some level.

The view of a system as a set of interconnected elements is what has been called the "systems approach" to problem solving. With this approach, the analysis focuses on how connections between the elements influence the overall behavior of the system. Its viewpoint implies a willingness to accept a less detailed description of the operation of the individual elements in order to achieve this overall understanding. This viewpoint can be applied to the study of either man-made or natural systems. It reflects the belief that the behavior of complex systems is made up of basic behavior patterns that are contributed by each element and that can be studied one at a time.

The behavior of an element is specified by its input-output relation, which is a description – usually mathematical – of how the output is affected by the input. An input is a cause; an output is an effect due to the input. Thus the input-output relation expresses the cause-and-effect behavior of the element. The system itself can have inputs and outputs. These are determined by the selection of the system's boundary. Any causes acting on the system from the world external to this boundary are considered to be system inputs. Similarly, a system's outputs can be the outputs from any one or more of the elements, viewed in particular from outside the system's boundary.

There are two types of elements or systems: static and dynamic. A static element or system is one whose output at any time depends only on the input at that time and which responds instantaneously to the input at that time. Ohm's Law, $e = iR$, describes the physical situation of a resistor quite well when the applied voltage is constant. But when the applied voltage is changing with time, it predicts that the current will change instantaneously proportional to the applied voltage. This is physically not possible. It is an approximation, an idealization, as nothing is instantaneous in the real world. A dynamic element or system is one whose present output depends on past inputs. Any system that contains at least one dynamic element is a dynamic system.

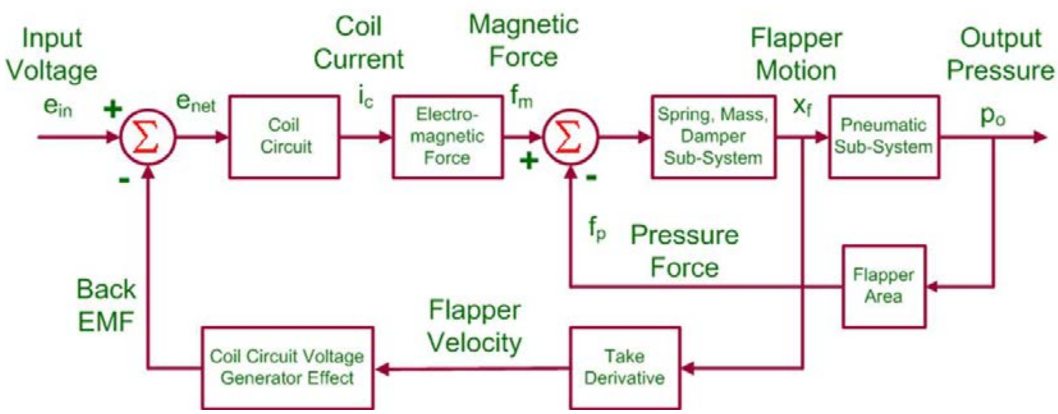
In the study of dynamic engineering systems, we deal with entire operating machines and processes rather than just isolated components and we treat the dynamic behavior of mechanical, electrical, magnetic, fluid, thermal, and combined systems. We strive to emphasize the behavioral similarity among systems that differ physically and develop general analysis and design tools useful for all kinds of physical systems. This serves as a unifying foundation for practical application areas. In our desire for physical insight, we often sacrifice detail in component descriptions so as to be able to better understand the behavior of complex systems. This also allows us to better design and optimize complex systems, as we are using as few essential parameters as possible in the system description. We use methods which accommodate component descriptions in terms of experimental measurements when accurate theory is lacking or too complex and develop universal lab test methods for characterizing component behavior. It is common practice that as components are built or purchased, they are tested to determine accurate parameter values needed for overall system design.



Electro-Pneumatic Transducer: An Engineering System

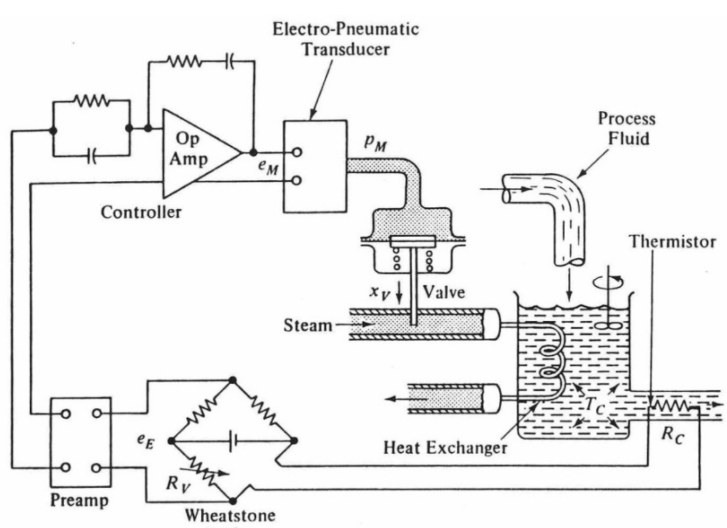
Note the <u>three methods of engineering communication</u>: picture, schematic, & block diagram!

Block Diagram of an Electro-Pneumatic Transducer



Engineering dynamic systems can be small-scale, as the electro-pneumatic transducer above is, and large-scale. The engineer designing the electro-pneumatic transducer to meet some desired performance specifications is very much interested in its detailed operation, as it is those details that determine its overall performance. To that engineer, this is an engineering dynamic system.

But to the designer of a temperature feedback control system for a chemical process, this transducer might be treated as an off-the-shelf component used to convert an electrical voltage to a pressure that would position a steam-flow control valve for a heat exchanger. The detailed operation of the electro-pneumatic transducer is not of interest here; only its overall simplified input/output relation is required.



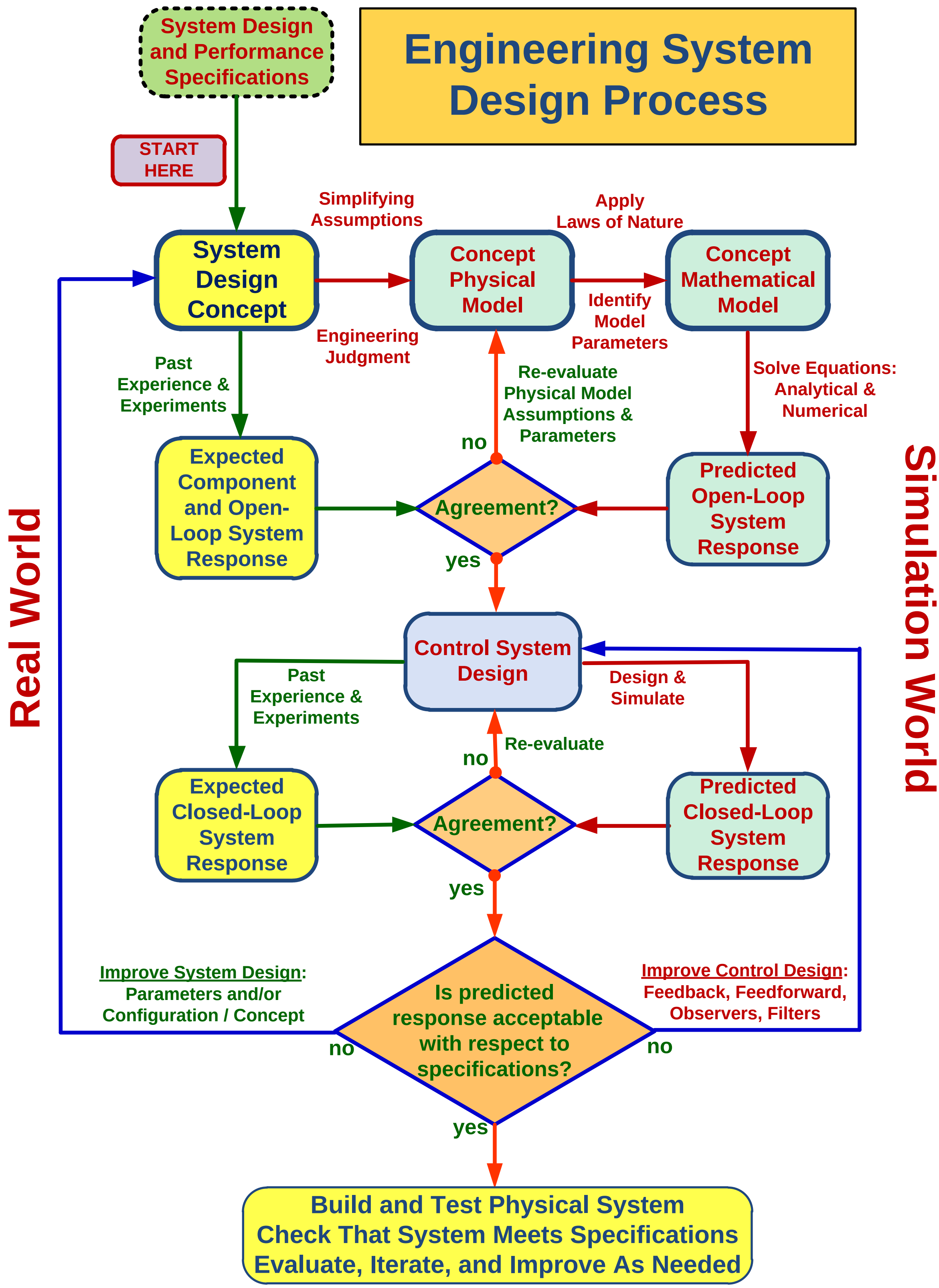
Multidisciplinary Engineering Dynamic System Example

A transducer is a device that transforms one type of energy to another. The electro-pneumatic transducer transforms electrical energy into fluid energy. The purpose of this device is to accept an input voltage signal e_{in} in the range 3-15 volts and produce a closely proportional output air-pressure signal p_o in the range 3-15 psig. This multidisciplinary engineering dynamic system has mechanical, electrical, magnetic, and fluid elements.

In this device, the input, or command, voltage e_{in} is applied to the coil of wire, causing a current i_c to flow in the wire. Since this current lies in the magnetic field of the permanent magnet, the coil feels a magnetic force f_m. The coil is rigidly attached to the vertical rod which is constrained to move vertically by the two leaf springs which are cantilever beams. A cantilever beam is a beam fixed at one end, but free to move at the other. For small motions, that free-end motion is approximately vertical. The cantilever beam acts mainly like a spring. This force causes the coil and vertical rod to move, bringing the flapper closer to the air nozzle and raising the output pressure p_o. The resulting coil and rod motion is opposed by the leaf-spring (the cantilever beam which acts like a spring) force proportional to coil and rod displacement and the fluid damping, energy-dissipating force (to reduce unwanted oscillations) proportional to the coil and rod velocity. The coil / rod mass, leaf springs, and damper / float device comprise what is called a mass-spring-damper system. The pressure, acting over the flapper area A_p, causes a force f_p which opposes f_m. We have seen one electromechanical effect in this device, the motor effect, which says that the passage of current through the coil causes it to experience a magnetic force proportional to the current. There is another electromechanical effect present here, the generator effect. It says that the motion of the coil through the magnetic field causes a voltage proportional to velocity to be induced into the coil. This is called the back electromotive force (back emf).

For a steady (not time-varying) input voltage, the system will produce an output pressure such that the forces are balanced and equilibrium exists. Thus, we can conveniently control the pressure by changing the input voltage. Desirable performance characteristics of such a transducer include linearity (output pressure proportional to input voltage) and adequate speed of response. In addition to the one controlled input to the system, the input voltage e_{in}, there are possible undesired inputs that must also be considered. For example, the ambient temperature will affect the electric coil resistance, the permanent magnet strength, the leaf-spring stiffness, the damper-oil viscosity, the air density, and the dimensions of the mechanical parts. All these changes will affect the system output pressure p_o in some way, and the cumulative effects may not be negligible.

A block diagram is used to describe the electro-pneumatic transducer system. A block diagram of a system is a pictorial representation of the functions performed by each component and of the flow of signals. It depicts the interrelationships that exist among the various components. Inside each block is a description in words or equations of what that component does. It is easy to form the overall block diagram for the entire system by merely connecting the blocks of the components according to the signal flow. It is then possible to evaluate the contribution of each component to the overall system performance. A block diagram contains information concerning dynamic behavior, but it does not include any information on the physical construction of the system. The block diagram, along with words and sketches, are most effective communication tools all engineers must have in their toolboxes.



Engineering System Design Process
System Design and Performance Specifications
START HERE
System Design Concept
Simplifying Assumptions
Engineering Judgment
Concept Physical Model
Apply Laws of Nature
Identify Model Parameters
Concept Mathematical Model
Solve Equations: Analytical & Numerical
Past Experience & Experiments
Expected Component and Open-Loop System Response
Re-evaluate Physical Model Assumptions & Parameters
no
Agreement?
yes
Predicted Open-Loop System Response
Real World
Simulation World
Control System Design
Past Experience & Experiments
Design & Simulate
Re-evaluate
no
Expected Closed-Loop System Response
Agreement?
yes
Predicted Closed-Loop System Response
Improve System Design: Parameters and/or Configuration / Concept
Improve Control Design: Feedback, Feedforward, Observers, Filters
no
Is predicted response acceptable with respect to specifications?
no
yes
Build and Test Physical System
Check That System Meets Specifications
Evaluate, Iterate, and Improve As Needed

Engineering System Design Process

A Model-Based Design Approach from Concept to Working System

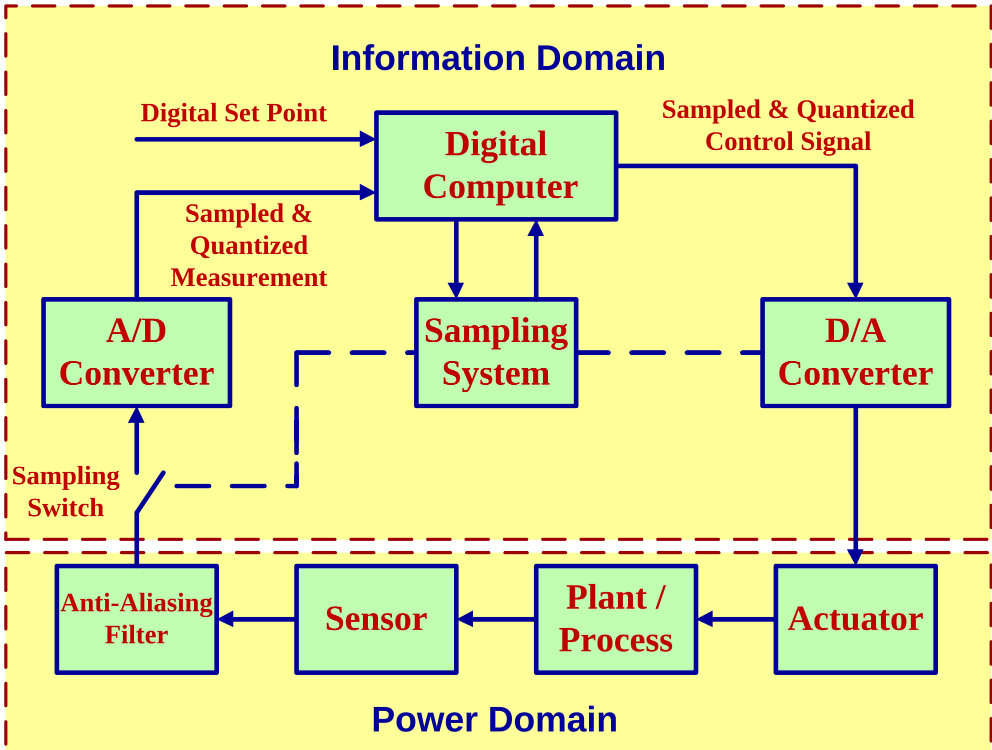
The top two drivers in industry today for improving development processes are shorter product-development schedules and increased customer demand for better-performing products. As engineering systems are becoming ever more multidisciplinary and complex, can these two goals be achieved at the same time? Challenges inhibiting product and system development fall into two categories: the multi-domain nature of the complete system and integration of the domains, and finding errors early in the development cycle and testing before hardware is available. Once a system is in development, correcting a problem costs 10 times as much as fixing the same problem in concept. If the system has been released, it costs 100 times as much.

The Engineering System Design Process addresses these challenges. Through system modeling and simulation, it facilitates: understanding the behavior of the proposed system concept; optimizing the system design parameters; developing optimal control algorithms, both local and supervisory; testing control algorithms under various scenarios; and qualifying the production controller with a simulated version of the plant running in real time (hardware-in-the-loop testing), before connecting it to the real plant.

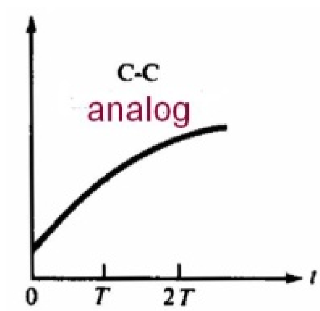
The Engineering System Design Process provides an environment that is rich with numerical and graphical analysis and design tools that stimulate innovation and cooperation within design teams. It aims to reduce the risk of not meeting the functional requirements by enabling early and continuous verification throughout the entire design workflow.

Don't Let This Happen To You!

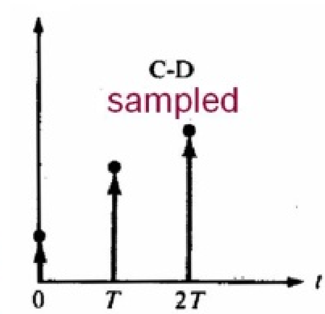
The Engineering System Design Process guides engineers in the solution of real-world problems.



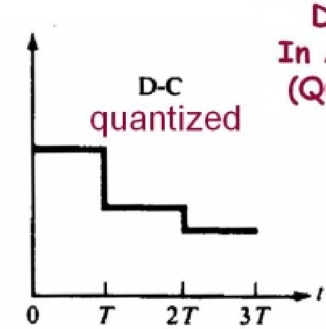
Modern Multidisciplinary Engineering System

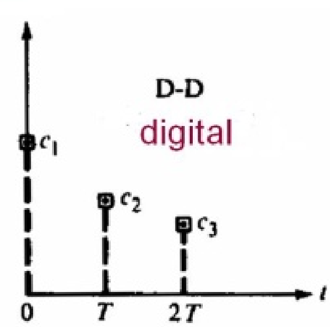


Classification Of Signals



	Continuous In Time	Discrete In Time (Sampled)
Continuous In Amplitude	C-C	C-D
Discrete In Amplitude (Quantized)	D-C	D-D





Mama Don't Take My Kodachrome Away!

Photographs do give us nice bright colors and the greens of summer and they do make you think all the world's a sunny day! But we don't need Kodachrome film anymore, as the digital image sensor – the heart of all digital cameras – has replaced film. It is the component that converts the light coming from the subject being photographed into an electronic signal. If you have a roll of Kodachrome film, you could not get it developed anywhere in the world! On December 30, 2010, at Dwayne's Photo in Parsons, Kansas, the last rolls of Kodachrome film in the entire world, with all those "nice bright colors," were processed. This is hard to believe, yet it is true, and it dramatically shows how digital the world has become. But how many people, engineers included, really understand the difference between the analog and digital worlds and the key issues involved in going from one to the other? For some it is just a curiosity, but, for all engineers, it is an absolute necessity.

Why do wagon wheels in a movie sometimes appear to rotate backward while the wagon is actually moving forward? When you hear music in the background while on a cell phone, why does the music sound flat or distorted? The answers to questions like these are found in understanding the fundamental concepts of digitization – sampling, aliasing, and quantization. The top diagram shows a computer-controlled system and the interface between the analog power domain and the digital information domain. Digitization, or analog-to-digital (A/D) conversion, is the act of converting an analog signal – continuous in both time and amplitude – to a digital signal – discrete in both time and amplitude. Discrete values in time are the result of sampling an analog signal and discrete values in amplitude are the result of representing those values using a finite number of bits (quantization). The bottom diagram shows the classification of signals.

There are a few fundamental concepts that every engineer needs to understand very well. Fourier showed that any waveform that exists in the real world can be generated by adding up sine waves of different amplitudes, frequencies, and phases, and that representation is unique. And Nyquist showed that a sampled signal can be converted back to its original analog signal without any error if the sampling rate is more than twice as large as the highest frequency of the signal. The digital-to-analog (D/A) converter accomplishes that task. If this Nyquist Sampling Theorem is violated, an inevitable, irreversible effect called aliasing results. Aliasing cannot be completely eliminated, only reduced with an anti-aliasing analog filter before sampling takes place. The effect of aliasing is that frequencies above the Nyquist frequency (½ the sampling frequency, also called the folding frequency) are folded back into the useful frequency range and appear indistinguishable from the real signals. For example, a tone 1 KHz above the Nyquist frequency will fold back to 1 KHz below, while a tone 1 KHz below the sampling frequency will appear at 1 KHz. The control system will respond to both signals – real and fictitious. The anti-aliasing filter will limit performance because of time delay, but the effects of aliasing are much worse.

The accuracy achieved in a digital memory device depends on the number of bits used for storage of each sample. Quantization is the process of changing the sample values to discrete levels and results in errors called quantization noise, because the effect sounds like noise in a digitized music signal and looks like noise in a digital image. The measure of the relative size of quantization noise is called the signal-to-noise ratio (SNR) and it is given by a simple formula $SNR = 2^B$, where B is the number of bits used to store samples.

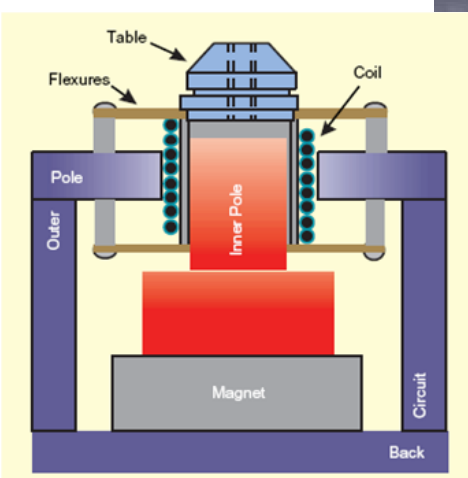
Less Real, Less Complex, More Easily Solved

Truth Model	Control-Oriented Model	Design Model

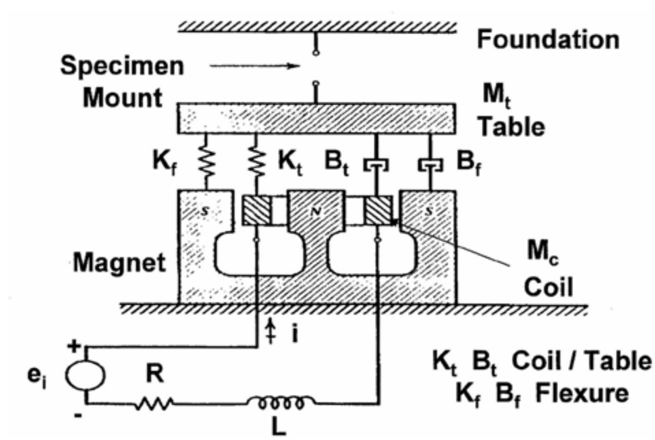
More Real, More Complex, Less Easily Solved

Hierarchy of Physical Models

Electrodynamic Vibration Exciter



Physical System



Physical Model

The Purpose of Modeling Is INSIGHT !

Modeling: The Key Element in Modern Engineering Practice

In design an engineer rarely starts with a blank sheet of paper. Designs are usually the result of the improvement of an existing system, the innovative combination of existing systems, or the application of new technology or new knowledge to an existing system. In all this, understanding what exists is paramount and modeling is essential to that understanding. The purpose of modeling is insight! Also once a concept has been developed in the conceptual phase of design, it is evaluated through modeling – not by building and testing – the physical system, sensors, actuators, and controls, all integrated into the design concept. No after-thought add-ons are allowed!

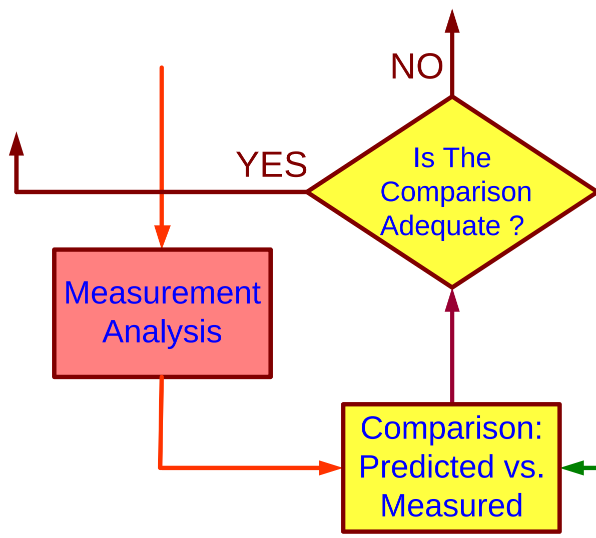
Ask six engineers what a model is and you may get six different answers. The word model has a specific meaning and modeling is the single most important activity in the modern multi-disciplinary engineering system design process. There are actually two distinct models of an actual dynamic physical system: a physical model and a mathematical model, and the distinction between them is most important. In general, a physical model is an imaginary physical system – a slice of reality – and in modeling dynamic physical systems we use engineering judgment and simplifying assumptions to develop a physical model. The challenges to physical modeling are formidable as the dynamic behavior of many physical processes is very complex. There is a hierarchy of physical models of varying complexity possible (top diagram), from the less-real, less-complex, more-easily-solved design model to the more-real, more-complex, less-easily-solved truth model, with a control-oriented model in between. The complexity of the physical model depends on the particular need, e.g., system design iteration, control system design, control design verification, physical understanding. Always ask the question: Why am I modeling? An excellent analogy is geographic maps and the varying detail one can display on a map. As an example, an electrodynamic vibration exciter is shown (middle picture), along with a schematic of that system, and a physical model of the physical system.

The intelligent use of simple physical models requires that we have some understanding of what we are missing when we choose the simpler model over the more complex model. The astuteness with which simplifying approximations are made at the onset of an investigation is the very crux of engineering analysis. The ability to make shrewd and viable approximations which greatly simplify the system and still lead to a rapid, reasonably accurate prediction of its behavior is the hallmark of every successful engineer. Once a physical model has been developed, the appropriate laws of nature, e.g., Newton's Laws, Maxwell's Equations, Conservation of Mass and Energy, are applied to the physical model to generate the mathematical model, i.e., the differential equations describing the dynamic behavior of the physical model.

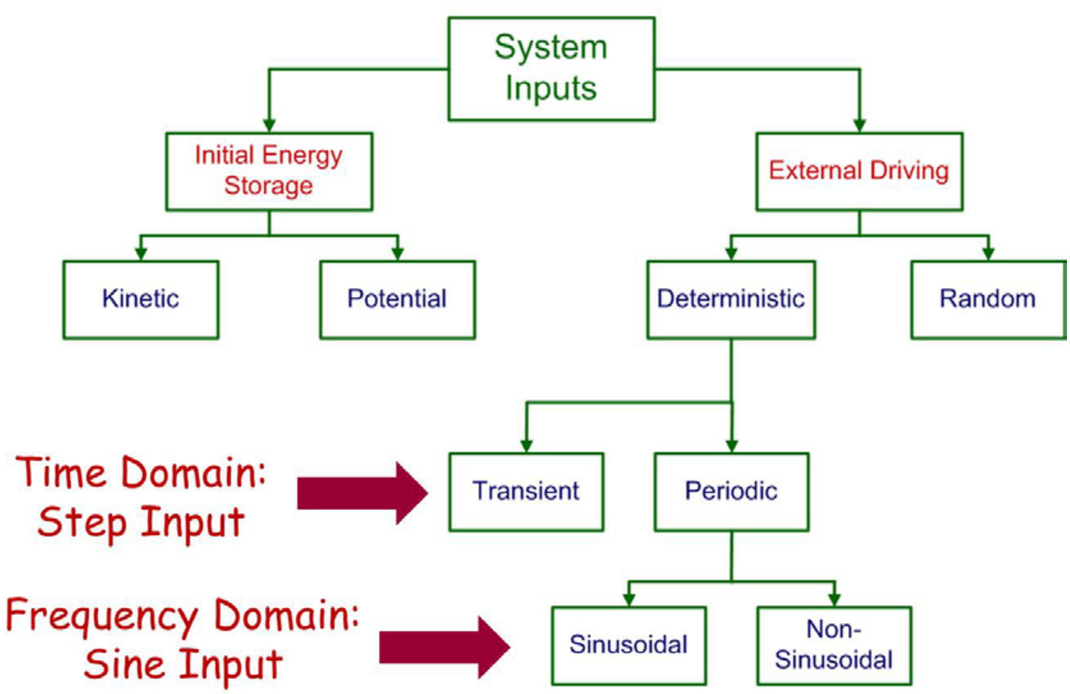
- Model-Based System Design re-engineers the traditional development process from one which is paper-based to one that uses an executable model that is the repository for all information about the concept, design, and implementation.
- The model is used throughout the four stages of development: research, design, implementation, and verification and validation.
- At each stage of development the model is updated and elaborated ensuring continuity and traceability throughout the evolution of the design.
- In its most basic form, model-based system design is the use of models to describe the specifications, operation, and performance of a component or system of components.

System Inputs

What is the input to the actual physical system that we are measuring the response to?
What is the input to the mathematical model that we are predicting the response to?
Of course, these two inputs must be the same if we are to compare the measured response to the predicted response.
Are there standard inputs used by engineers in the investigation process?
If so, what are they? Why are they effective? Why not use the actual real-world inputs?



Classification of System Inputs



System Inputs

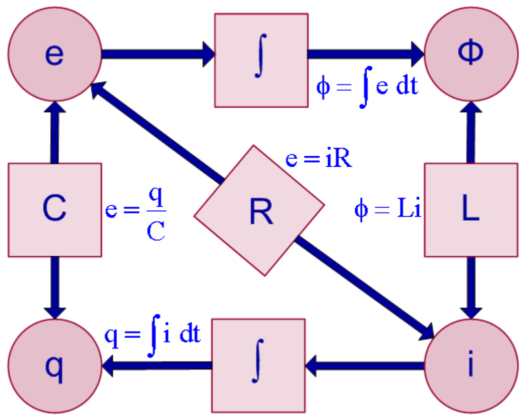
The model of the physical system under investigation, both physical and mathematical, must be validated if it is to be of any use. How does an engineer validate a model of a physical system? In order to validate the physical and mathematical model of the physical system under investigation, the engineer must first cause the system to respond. This is done by introducing to both the system model and to the actual physical system an input. An input is simply some action which will cause the system to respond. The same input is introduced to both the mathematical model and to the physical system. The predicted response is obtained by solving the mathematical model, i.e., the equations describing the behavior of the physical model, with the designated input. The actual response is obtained by introducing into the actual physical system the designated input and measuring the response using instruments like multi-meters, oscilloscopes, or dynamic signal analyzers (top diagram). What types of system inputs are there? One possible classification of system inputs is shown (bottom diagram). The two main classifications of system inputs are initial energy storage and external driving.

Initial energy storage refers to a situation where the engineer puts a system, initially in an equilibrium state, into a different state and then releases the system. The system then responds free from any external interference.

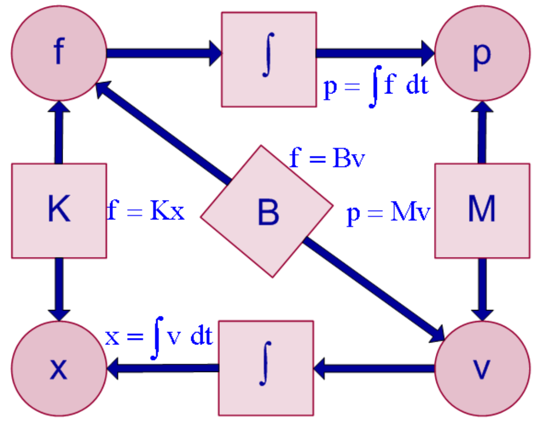
The other major classification of input is external driving. In this case, a physical quantity from the system's environment, i.e., from outside the system boundary, is applied to the system and causes it to respond. We often choose to study the system response to an assumed ideal source, which is unaffected by the system to which it is coupled, with the view that practical situations will closely correspond to this idealized model. External inputs can be broadly classified as deterministic or random, recognizing that there is always some element of randomness and unpredictability in all real-world inputs. Deterministic input models are those whose complete time history is explicitly given, as by mathematical formula or a table of numerical values. This can be further divided into two categories. A transient input model is one having any desired shape, but existing only for a certain time interval, being constant before the beginning of the interval and after its end. The second type of deterministic input is a periodic input model. This input type repeats a certain wave form over and over, ideally forever, and is further classified as either sinusoidal or non-sinusoidal.

Random input models are the most realistic input models and have time histories which cannot be predicted before the input actually occurs, although statistical properties of the input can be specified. When working with random inputs, there is never any hope of predicting a specific time history before it occurs, but statistical predictions can be made that have practical usefulness.

As the precise mathematical functions for actual real-world inputs will not generally be known in practice, engineers typically use two inputs to evaluate dynamic systems: a step input and a sinusoidal input. These two input types lead to the two views of dynamic system response: time response and frequency response. Experience with the actual performance of various classes of systems has established a good correlation between the response of systems to these standard inputs and the capability of the systems to accomplish their required tasks. In addition, simplicity of form of standard inputs facilitates mathematical analysis and experimental verifications. Also, design is much concerned with comparison of competitive systems. This comparison can often be made nearly as well in terms of standard inputs as for real inputs.

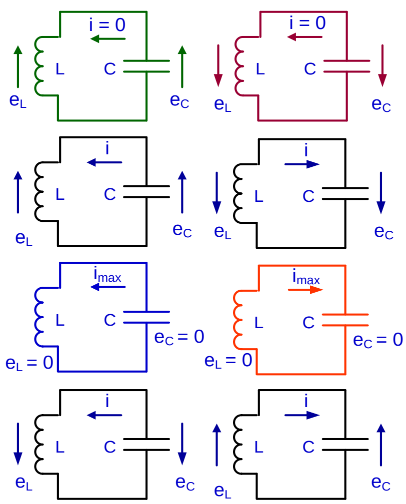


Model Structure for Electrical Systems

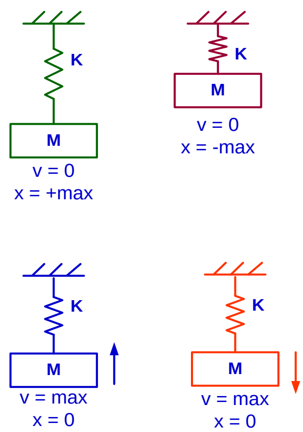


Model Structure for Mechanical Systems

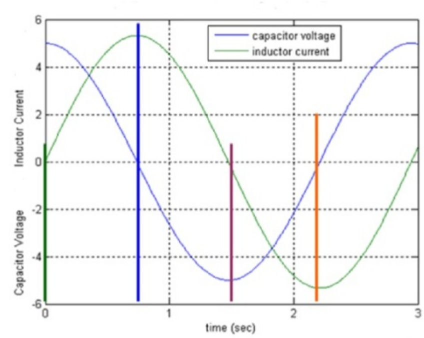
ANALOGIES



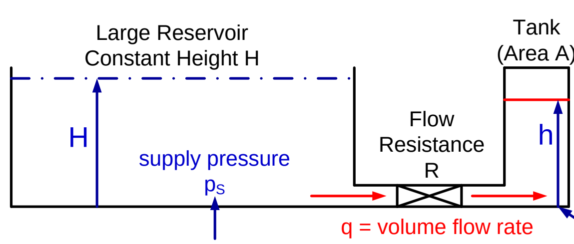
Inductor-Capacitor



Spring-Mass



Mechanical-Hydraulic Analogy



$p_S = \text{constant} = \rho g H$ (bottom of reservoir)

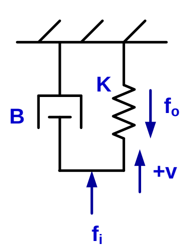
$\rho =$ fluid density

$g =$ acceleration due to gravity

$p_{tank} = \rho g h$

$$C = \frac{A}{\rho g}$$

$$\boxed{RC\frac{dh}{dt} + h = H}$$



$$\boxed{\frac{B}{K}\frac{df_o}{dt} + f_o = f_i}$$

$$\boxed{\tau\frac{de_{out}}{dt} + e_{out} = Ke_{in}}$$

Analogies Give Engineers Insight

Insight based on fundamentals is the key to innovative multidisciplinary problem solving

A person trying to explain a difficult concept will often say "Well, the analogy is …" The use of analogies in everyday life aids in understanding and makes everyone better communicators. Engineering systems depend on the interactions among mechanical, electrical, magnetic, fluid, thermal, and chemical elements, and most likely combinations of these. They are truly multidisciplinary and the designers of these systems are from diverse backgrounds. Knowledge of physical system analogies can give design teams a significant competitive advantage.

Consider the exhaust system of a motorcycle and its heat shield. Temperatures have to be controlled through design for performance, but also to protect the rider. Being able to model this system as a network of thermal resistances and capacitances, just like an electrical circuit, is a powerful design tool. It allows the engineer to visualize the flow of heat and the storage of thermal energy, and specify key temperatures by selection of materials and geometries that vary the network thermal resistances (conduction, convection, and radiation) and capacitances.

Some industrial systems require maximum heat transfer (computer cooling), and others minimum heat loss (hot water/steam boiler). Improving performance happens with understanding – not by trial and error – and quickly. Applications from printed circuit boards to human body thermal analysis make use of this technique.

To explore in some depth the nature of physical system analogies, let's use the common electrical-mechanical analogy (top diagram). These systems are modeled using combinations of pure (only have the characteristic for which they are named) and ideal (linear in behavior) elements: resistor (R), capacitor (C), and inductor (L) for electrical systems and damper (B), spring (K), and mass (M) for mechanical systems. The variables of interest are voltage (e) and current (i) for electrical systems, and force (f) and velocity (v) for mechanical systems. The analogy is obvious!

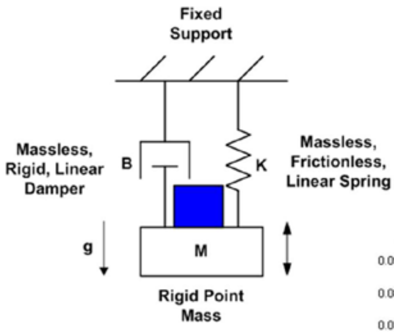
We can use this analogy to explain the flow of current and the changes in voltages in a LC (inductor-capacitor) electrical circuit – difficult to envision for most mechanical engineers and even for some electrical engineers – by comparing it to a spring-mass mechanical system (middle diagram). The diagram is color-coded: green, blue, purple, and orange diagrams for each system correspond to each other, as do the vertical lines on the graph indicating capacitor voltage and inductor current at the four specific instances. By comparing the motion of the mass – its changing potential energy corresponding to energy stored in the electric field of the capacitor and its changing kinetic energy corresponding to energy stored in the magnetic field of the inductor – one can better understand how electrical capacitors and inductors function.

Analogies do not always involve an electrical analog of some other system, although that is most common. The bottom diagram shows a hydraulic system and its mechanical analog.

For enhanced multidisciplinary engineering system design and better communication and insight among the design team members, the use of analogies is a powerful addition to an engineer's toolbox.

What's Your Point of View?

Time Domain



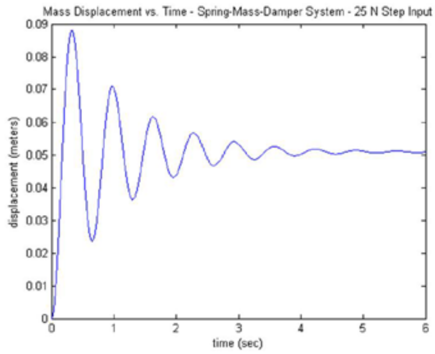
Step Input

The system is "at rest" at time t = 0 and we instantly change the input quantity, from wherever it was just before t = 0, by a given amount, either positive or negative, and then keep the input constant at this new value "forever."

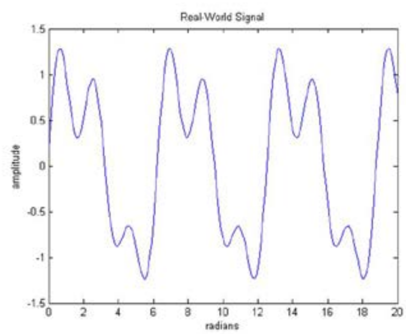
Time Domain

We measure how long something takes.

Step Response



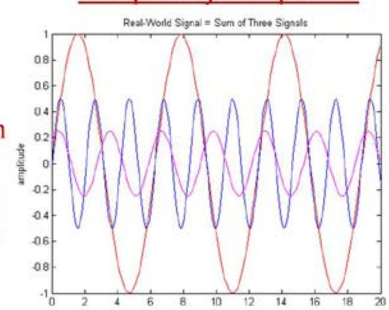
Frequency Domain



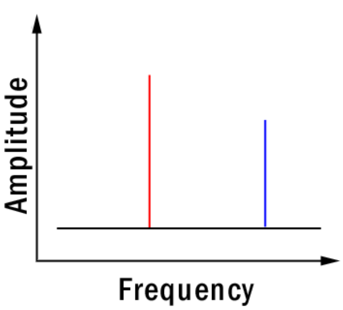
Frequency Domain

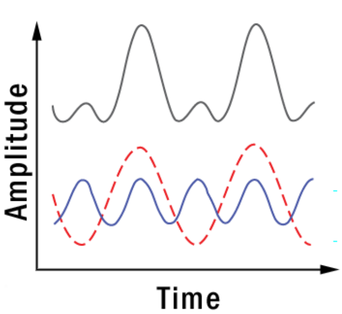
We measure how fast or slow things are happening.

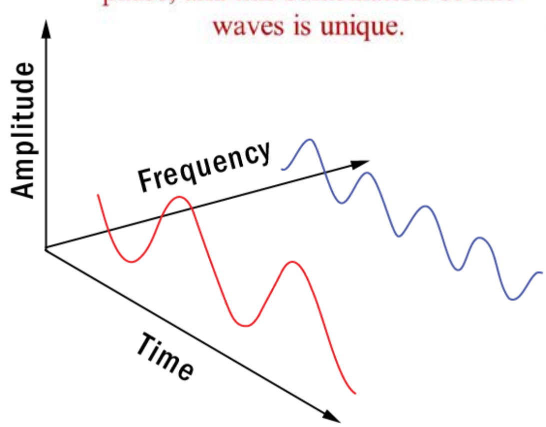
Frequency Response



Any real-world signal can be broken down into a sum of sine waves of varying frequency, amplitude, and phase, and this combination of sine waves is unique.







Time and Frequency Domains

What’s Your Point of View?

Time, Frequency, and Modal Domains Offer Complementary Views and Insight!

As multidisciplinary teams are formed to solve complex problems, insight and communication are of utmost importance. We have all witnessed how engineers from different backgrounds describe the same concepts using different language and different points of view which often can lead to confusion and ultimately design errors. Being able to describe concepts, with clarity and insight, in a variety of ways is essential for every engineer.

The three domains – time, frequency, and modal – represent different perspectives. They are interchangeable, complementary points of view, i.e., no information is lost in changing from one domain to another, and together lead to better understanding and insight.

Most signals and processes involve both fast and slow components happening at the same time. In the time domain (temporal) we measure how long something takes, whereas in the frequency domain (spectral) we measure how fast or slow it is. The modal domain breaks down complicated structural vibration problems into simple vibration modes. No one domain is always the best answer, so the ability to easily change domains is quite valuable and aids in communication among engineers from different disciplines.

The time domain is a record of the response of a dynamic system as indicated by some measured parameter, as a function of time (top figure). Over one hundred years ago, Jean Baptiste Fourier showed that any real-world signal can be broken down into a sum of sine waves and this combination of sine waves is unique. By picking the amplitudes, frequencies, and phases of these sine waves, one can generate a waveform identical to the desired signal (middle figure).

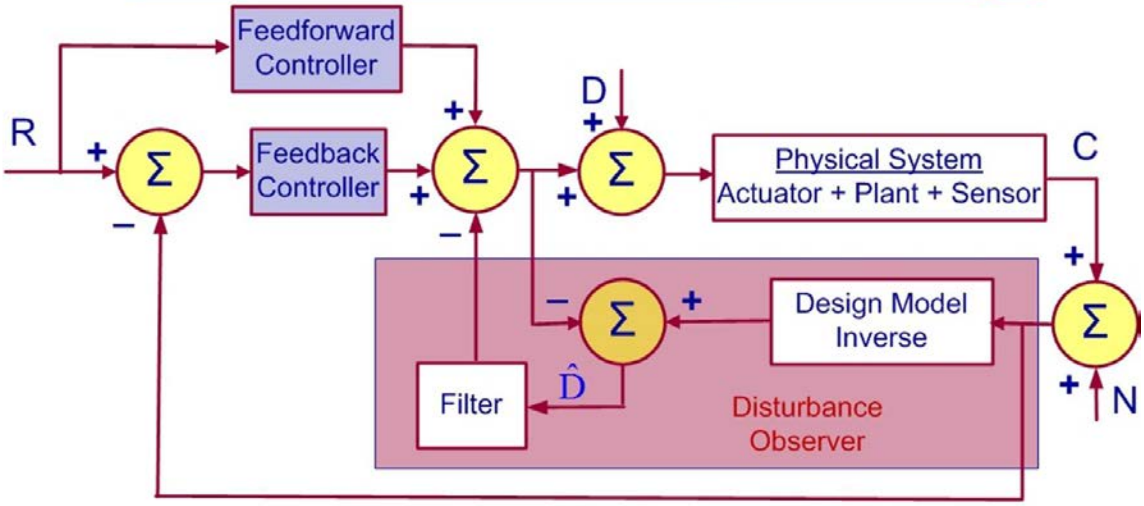
To show how the time and frequency domains are the same, the bottom figure shows three axes: time, amplitude, and frequency. The time and amplitude axes are familiar from the time domain. The third axis, frequency, allows us to visually separate the sine waves that add to give us the complex waveform. Note that phase information is not represented here.

If we can predict the response of a system to a sine wave input, i.e., the frequency response, then we can predict the response of the system to any real-world signal once we know the frequency spectrum of that signal. The system’s frequency-response curves are really a complete description of the system’s dynamic behavior.

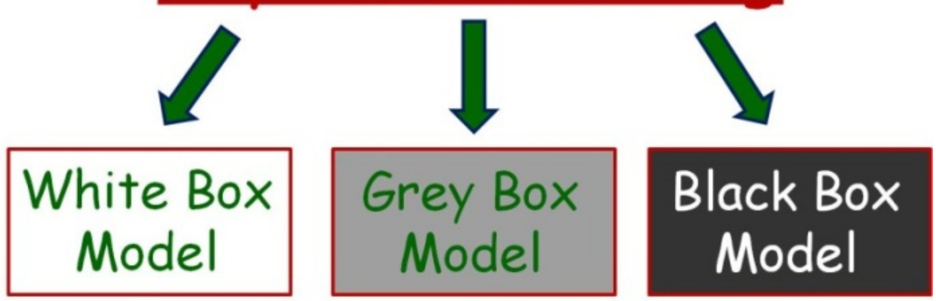
Engineers who can bridge gaps among disciplines and articulate complementary points of view clearly and insightfully will certainly have a competitive advantage.

To understand the modal domain, consider a simple mechanical structure – a tuning fork. When struck (force impulse), the mechanical vibration causes sound waves and its tone tells us that it is primarily vibrating at a single frequency. The time domain view of the sound caused by the deformation of the fork is a lightly-damped sine wave. The frequency domain view shows a major peak that is very lightly damped, which is the tone we hear. There are also several smaller peaks. Each of these peaks, large and small, corresponds to a vibration mode of the tuning fork. Just as we can represent a real waveform as a sum of much simpler sine waves, we can express the vibration of any structure as a sum of much simpler vibration modes. The task of modal analysis is to determine the shape and the magnitude of the structural deformation in each vibration mode. Once these are known, it usually becomes apparent how to change the overall vibration.

State-of-the-Art Control Design



Physical Modeling



White Box Model	Grey Box Model	Black Box Model
Physical Model based entirely on First Principles	Physical Model based on First Principles & Experimental Measurements	Physical Model based entirely on Experimental Input-Output Measurements

Control Design: Pervasive and Perplexing

Control is a hidden, enabling technology that is present in almost every engineered system today. Despite this fact, control system design is still mysterious and often falls in the domain of a specialist. Today, every engineer must know how to design, implement, and integrate a control system into a design from the start of the design process. An engineer needs to understand how to balance performance, low cost, robustness, and efficiency to effectively accomplish these goals.

Evaluating a design concept is best done through modeling, not by building and testing, as modeling provides true insight on which to base design decisions. There is a hierarchy of models possible of varying complexity and fidelity, but a simple design model which captures essential attributes is the most useful, i.e., dominant dynamics. An integrated control system can enhance a design through stabilization, command following, disturbance and noise rejection, and robustness. All of this can be accomplished through a combined approach (top diagram), rather than trying to accomplish all with a single feedback controller, as is too often the case.

The design model is typically used for both feedback and feedforward controller design. However, in practice, the physical system will deviate from that design model. A disturbance observer regards any difference between the physical system and the design model as an equivalent disturbance applied to the model. It estimates the disturbance and uses it as a cancellation signal. So in addition to enhancing disturbance rejection, the disturbance observer makes the physical system behave like the design model over a certain frequency range, thereby simplifying the design of the feedback and feedforward controllers. Since the design model inverse is not realizable, a unity-gain, low-pass filter, specifying the observer bandwidth, is added.

Next, the feedback controller is designed solely to force dynamic consistency by mitigating the effects of model uncertainty and disturbances, usually with high gain and integral control. A common mistake is made in designing the feedback controller for desired output with no regard for robustness, only to find poor performance when applied to the physical system. However, once consistency is enforced, the desired output can be augmented with a feedforward controller, typically the dynamic model inverse, to recover the dynamic delay of the closed-loop system with no effect on stability or properties of the closed-loop system.

The combination of a disturbance observer with both feedback and feedforward controllers is not new and many researchers have demonstrated its effectiveness. What needs to be done now is to bridge that theory / practice gap and put this technique into the hands of the multidisciplinary systems engineers responsible for creating the innovative systems we all need.

Reality Check

In many present-day industrial applications, systems are built without modeling. Although the information to model the system as a white or grey box (bottom diagram) is in general available, this is often not done for many reasons, such as: lack of engineering skill to model a system, lack of time to model a system, pressure to build the system and make it work as quickly as possible, lack of understanding how important modeling is, lack of multidisciplinary knowledge to put it all together, and the very common mind set that as long as the system works, even if it is not optimized, it is good enough. So black box modeling is often used after the system is built to help in control system design.