Innovation and the Two Dilemmas

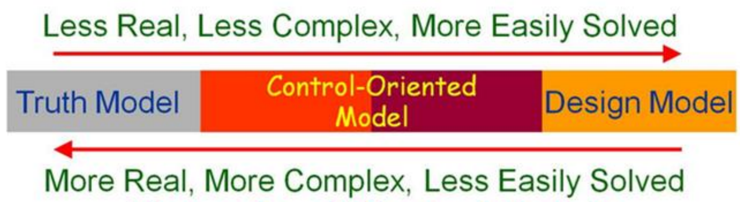
Model-Based Design and a Paradigm Shift are the Answers

Engineers, and the companies they work for, are facing an innovation crisis. *Innovate or Perish* is the mantra we often hear, but how can innovation happen when companies and their engineers are each facing a real dilemma, illustrated below?

The solution to these two dilemmas is a renewed focus on multidisciplinary model-based systems engineering – now known as *Mechatronics* – and a paradigm shift in the way education for the practicing engineer is delivered.

So what actually is model-based design and why is it the key to multidisciplinary engineering practice? A physical model of a design concept, based on simplifying assumptions (which change as the project progresses and one learns better what effects matter more than others), is created. This is an approximation of the real system and a hierarchy of models is possible depending on the reason for modeling. See figure below.

Model-Based Design



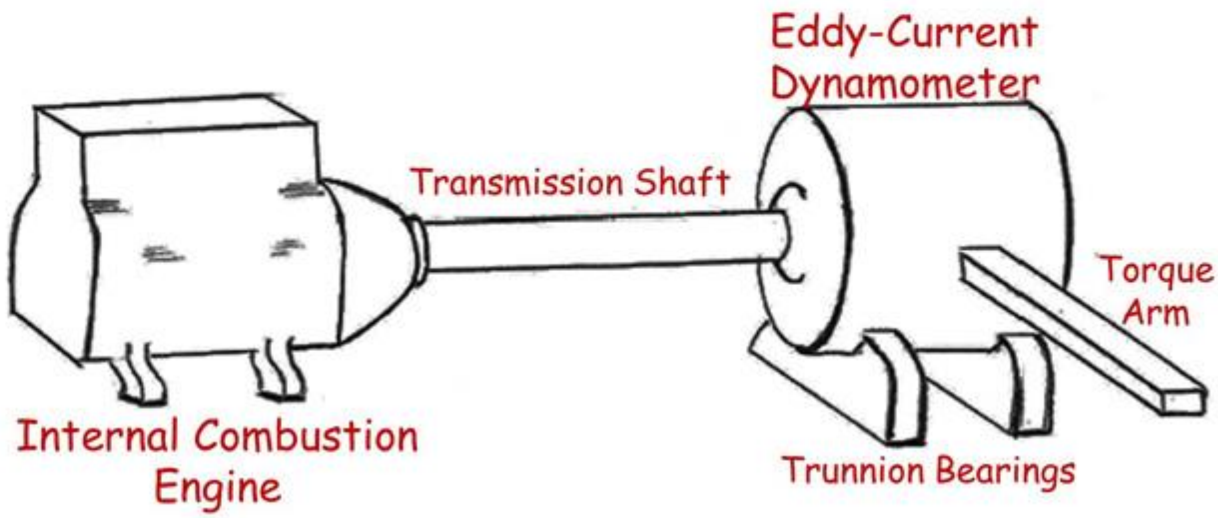
Hierarchy of Physical Models

Always Ask: Why Am I Modeling?
The Purpose of Modeling is INSIGHT!

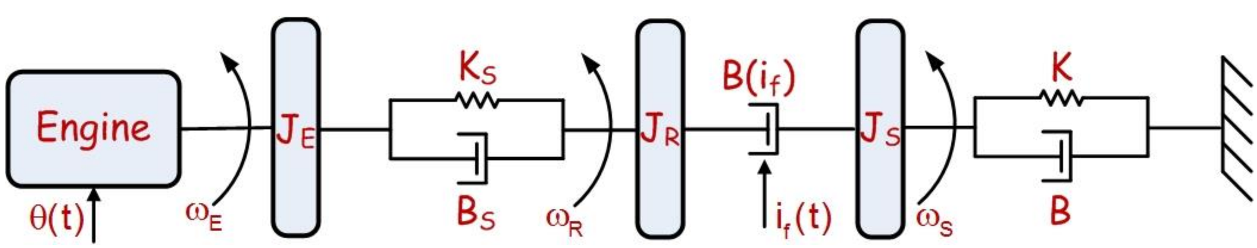
Laws of nature (e.g., Newton's Laws, Maxwell's Equations) are applied to the model, along with component model equations, to generate the equations of motion for the multidisciplinary engineering system. These equations – nonlinear and coupled – are solved in Simulink / SimMechanics / SimHydraulics / LabVIEW to predict how the model will behave when various inputs – desired and disturbance – are applied. These predictions are then verified either from experience or by some experimental testing. A control system is then designed based on this system model. The controlled system is simulated and again predictions need to be verified. At that point, changes can be made either to the system design or to the control design, as nothing has been built yet. Once a design – system + control – meets the performance requirements, then assumptions can be relaxed and parasitic effects can be added to bring the model as close to reality as possible. Response and actuation plots are the deliverables, along with model equations and the accompanying block diagrams. If this is not done, then the only alternative is to the take the concept, which existed only in animation form with no substance, and build it hoping for the best. How does one create this system without modeling? The only answer is – let's build it and see if it works. If one has done this before and has a lot of experience, maybe that approach will be successful. But if something happens that is not understood or there is a need to improve the performance of the system, there is no way to do that other than by trial and error and that leads to huge cost and still no understanding. In the end the deliverable is a working system along with a complete understanding of how the system works, so in the future it can be improved with minimal effort because one already understands how it works.

Can physical system modeling be taught? Is it an art or a science? Many engineers have little experience, and, hence, little confidence in doing it. Physical system modeling, either applied to an existing system or a concept in the design process, leads to thorough understanding, differentiates engineers, and gives companies a competitive advantage as it leads to innovation.

Often, engineers refer to modeling as mathematical modeling. That is misleading. A mathematical model is obtained by applying the laws of nature to the physical model, not to the physical system. The physical model must come first, and there is a hierarchy of physical models possible in response to the question: Why am I modeling? Engineering judgment and simplifying assumptions applied to the physical system lead to the physical model, which must capture the essential multidisciplinary attributes of the physical system. Hence, a working knowledge of multidisciplinary physics is essential. Always, the simplest model that meets the need is best. It is the modeling skills of the engineer that need to be enhanced, not the use of modeling tools! Here is an example.



The figure above shows an internal combustion engine connected to an eddy-current dynamometer. The physical model is shown below. The engine is considered a nonlinear angular velocity source (ω_E) modulated by the throttle setting $\theta(t)$. The main energy storage is associated with the rotating inertia J_E, lumped at the output of the engine shaft. The torque transmission shaft has compliance and energy dissipation, and is modeled with a rotational spring K_S and rotational damper B_S. The shaft inertia is neglected. The dynamometer consists of a toothed rotor J_R which rotates (ω_R) in the magnetic field created by passing current $i_f(t)$ through the stator windings. A voltage is induced in the conductive rotor rotating in the stator magnetic field (Faraday's Law). This induced voltage creates eddy currents in the rotor which generate a magnetic field (Ampere's Law) which opposes the stator magnetic field (Lenz's Law). The stator inertia J_S, mounted in trunnion bearings, is free to rotate, but is restrained by a torque arm to measure the torque developed. The spring K and damper B represent the compliance and energy dissipation associated with the torque measurement.



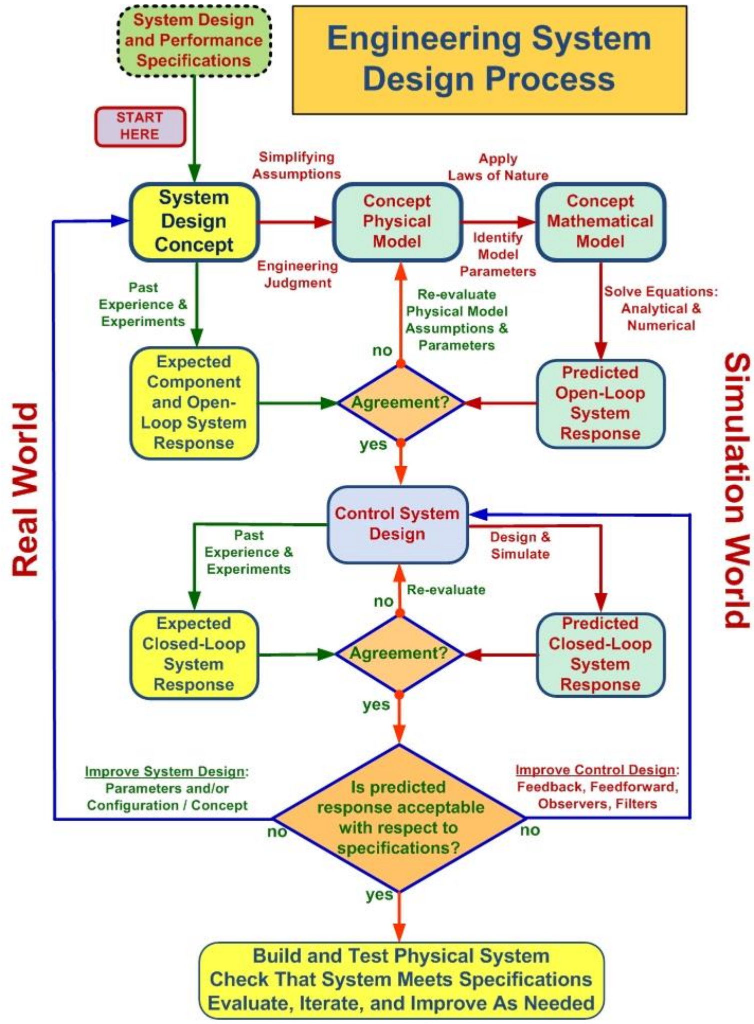
So successful physical modeling requires a fundamental understanding of multidisciplinary physics and a commitment to do it and not fall back on the old design-build-test approach. This is the most direct path to innovation.

Let’s now turn to education. If a young person wants to be a complete baseball player, he must be able to field, throw, run the bases, hit, and hit with power, and all these skills must be applied in an actual baseball game. To achieve this goal, he learns all these skills at the same time, improving gradually in each one while playing actual games and, over time, develops into a complete baseball player. The result is more than just the sum of the skills learned, but a sense of confidence and savvy that makes him a winner.   In multidisciplinary engineering practice, a model-based design approach is essential and the necessary skill set includes modeling and analysis of multidisciplinary dynamic engineering systems, including their digital control systems and their sensors and actuators with the necessary electronics. Theory and practice must be in balance when mastering these skills. If “playing a game” means putting these together (either virtually in a computer simulation or physically with an actual hardware system) to create a system to solve a problem, then that rarely happens in engineering education. We devote separate courses to each skill and somehow think that learning each skill very well will somehow magically enable the student to graduate and critically think, integrate it all, and solve a real-world problem. In the baseball analogy, this would be utter madness, yet in engineering education, it is routine.

The present situation then is that engineering education today is less effective in preparing students for multidisciplinary, model-based system integration and optimization – exactly what is needed by companies to become innovative and gain a competitive advantage in this global economy. While there is some movement in engineering education to change that, this change is not easy, as it involves a cultural change from the silo approach to a holistic approach. I have heard it said that is easier to move a cemetery than it is to change an engineering curriculum. Engineering schools for whom that is true might soon be buried in those cemeteries. If information is a commodity, and I believe that now it is, and if all engineering schools do is deliver that information, i.e., traditional course content in a lecture format, then those schools will cease to exist, as there is little impact on student learning and performance with that type of education. The senior capstone multidisciplinary design course, for example, too often becomes a design-build-test exercise with the emphasis on just getting something done. Students rarely break out of their disciplinary comfort zone and thus fail to experience true multidisciplinary system, model-based design. What is needed are model-based design activities, with a balance between theory and practice, between academic rigor and the best practices of industry, presented in an integrated way throughout the engineering curriculum that prepares students for true multidisciplinary system, model-based engineering at the senior level and beyond.

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 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.

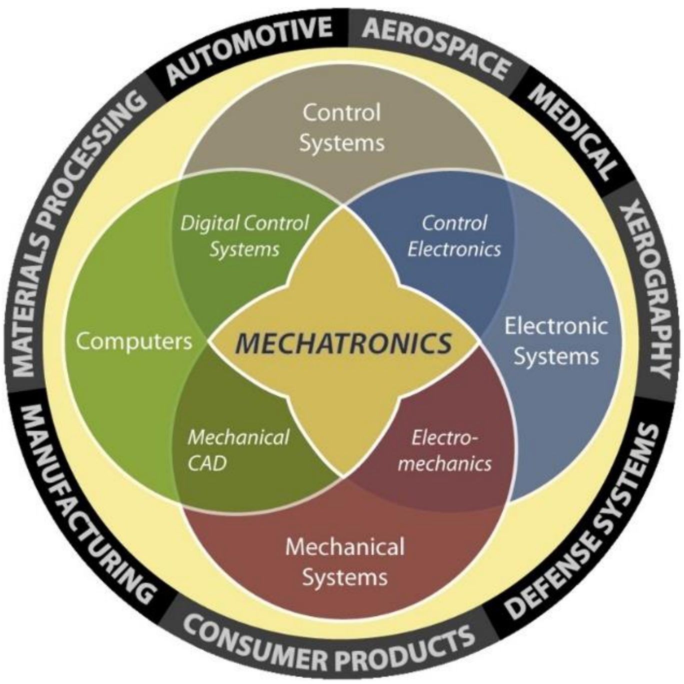
The Engineering System Design Process (figure on the right) addresses these challenges. Through system modeling and simulation, it facilitates: understanding the behavior of the proposed system concept; optimizing the system design parameters; developing optimal control algorithms, both local and supervisory; 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. The overarching theme in all engineering courses should be human-centered, model-based, multidisciplinary engineering problem solving. The key emphasis, in both class and studio, should be to strive to uncover the questions a student is asking himself / herself as he/she attempts to solve a problem and then give him/her the insight and understanding, based on physical principles and best industry practices, to ask the right questions. This requires quality time in studio with small groups of students working interactively, as well as a focus on applications of content in class rather than presentation of content.

In engineering design, a poorly designed physical system will never be able to give outstanding performance by adding a sophisticated controller. Similarly, traditional course content, even if delivered on line by the best lecturers in the world, is still just information, a commodity. The problem is not the delivery method; the problem is the content of the delivery. Engineering content must be rebundled and integrated with a balance between theory and industry best practice. That information then becomes knowledge that is not a commodity. It is this knowledge that stimulates students and transforms them into critical-thinking problem solvers resulting in a real competitive advantage in this global economy.

So while the challenges for engineering education are being talked about everywhere, the only way they will be solved is by changing culture – attitude and behavior – rejecting silos and comfort zones, and instilling ownership. Until engineering education is viewed as an equal partner with engineering research in achieving innovation, this will not happen.



Is there a new approach, a new paradigm, to engineering education? Yes, there is – at least a start of one for practicing engineers. Mechatronics is multidisciplinary systems engineering for the 21st century (see figure on the right). A newly created Mechatronics Certificate Program is an on-line program for companies who want to achieve a real competitive advantage in the global economy through superior engineering practice and better integration and collaboration with suppliers and customers. It will empower practicing engineers to significantly elevate their skill level with immediate tangible results to compete in the global economy. As traditional engineering skills and information are commodities today, this program is designed to exceed fundamental skills, with an integration of rigorous theory and best industry practice, to enhance engineering practice for companies competing to solve society's most urgent problems, and for engineers presently working in the trenches. Human-centered, model-based multidisciplinary design, grounded in mathematics and physics, is the key. Twelve one-credit, integrated modules, supported by multidisciplinary case studies, cover the essential areas of multidisciplinary system design (see figure on the right). This program is designed to be completed on-line in 12 months (one module per month), but it is much more than traditional on-line programs for two reasons: module integration / sequence and live contact through weekly two-hour, question-and-answer sessions via the internet, and monthly, half-day, end-of-module, on-site summary and laboratory hardware sessions.

The program consists of 12 one-credit, integrated modules taken in a specific order. Each module then is a prerequisite for the subsequent module. The 12 one-credit modules and the order in which they must be taken are:

- ✓ Physical and Mathematical Multidisciplinary Energy-Based Modeling
- ✓ Electrical Systems & Electronics for Power, Sensing, and Control
- ✓ Mechanical Systems: 2D and 3D Dynamics, Mechanical System Components
- ✓ Electro-Magnetic-Mechanical Systems
- ✓ Fluid Systems: Fluid Power Electro-Hydraulic Systems and Electro-Pneumatic Systems
- ✓ Thermal Systems
- ✓ Computer Simulation: MatLab, Simulink, SimHydraulics, SimMechanics, SimElectronics
- ✓ Measurement System Fundamentals, including NI LabVIEW and NI Hardware
- ✓ Sensors for Mechatronics: Mechanical, Electrical, Magnetic, Thermal, Fluid
- ✓ Actuators for Mechatronics: Brushed, Brushless, & Step Motors; Fluid Power Actuators
- ✓ Control System Fundamentals, including Programmable Logic Controllers
- ✓ Control System Design & Digital Implementation

The program learning outcomes include:

1. Engineers will learn the basic building blocks which comprise 21st-century multidisciplinary engineering systems, with a balance between academic rigor and best industry practices, and learn to integrate them into complete multidisciplinary engineering systems through various real-world case studies.
2. Engineers will experience the application of what they have learned in the formal modules to actual hardware systems at the end of each module in the Mechatronics Lab.
3. Companies will benefit by having an empowered mechatronics engineer who can serve as a catalyst for change and a mentor to other engineers.

Is this Mechatronics Certificate Program just a concept? It has been for several years. But now it will be offered by the Hofstra University School of Engineering and Applied Science (SEAS) Center for Innovation. The time is now for a change! This is just the beginning.