# Product Development with Virtual Prototypes

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For most research-funding organizations, computational engineering is a study area in academic engineering departments, and is often somewhat indistinguishable from highly applied physics, chemistry, and biology research. I'm going to address a different kind of computational engineering that is focused on the development, manufacture, and deployment of innovative, complex technical products such as computers, electronics, ships, and airplanes. Much of the current US prosperity is due to its lead in product innovation, especially in these types of high-technology products. Computing played an important role in establishing that lead and its role in sustaining the lead is growing. The construction and analysis of virtual prototypes with physics-based performance software tools utilizing high-performance computers offers US industries and government an opportunity to reduce the time, cost, and risks of developing, producing, and deploying complex, innovative technical products. The productivity gain from the use of virtual prototypes analyzed with physics-based performance prediction tools is a potential game changer for product development.

The potential game-changing effects of virtual prototyping can be understood within the context of the traditional systems engineering approach to product development and production (see Figure 1).

## The System Lifecycle Model

Concept development includes formulating and defining a system concept that meets a specific need.[1] Engineering development is turning the system concept into an engineering design that meets the need within cost and schedule constraints. Post-development includes manufacturing, deploying, and sustaining the system. The design of innovative new products require extrapolation of existing designs. These extrapolations are based on experience with existing systems; expert judgment; and "rules of thumb" and other simple analyses. Increasing the level of innovation increases the level of extrapolation, and the associated risk that the extrapolation will include too many uncertainties. Validating the design of innovative complex systems (automobiles, airplanes, and so on) requires physical testing that can only occur late in the process, chiefly in the engineering design/integration and evaluation phases, when partial and full-scale physical prototypes become available.

This product development paradigm traces its origin to the industrial revolution, if not before. Several centuries ago a simple version of a product (such as a steam engine) would be designed, constructed, and tested. The failures observed during testing would be analyzed,

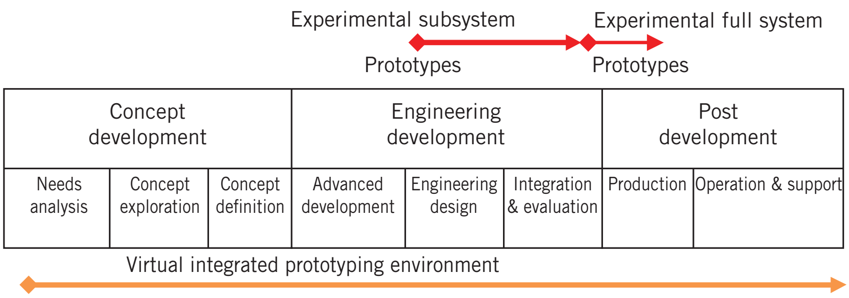


**Figure 1.** System lifecycle model for product development and production.[1]

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and the "design, build, test, fix" steps iterated until an acceptable design and product emerged, or funds and time ran out. As products become more complex and the level of extrapolation increases, this "design, build, test, fix" paradigm requires more iterations and time to converge. In addition, it becomes more difficult, if not impossible, to change the product requirements to respond to new needs, because the increased time and money required for rework to address new requirements and correct shortcomings are prohibitive.

### Moving to Virtual Prototyping

An alternative approach is emerging based on the use of "virtual" rather than physical prototypes. The virtual prototypes are digital representations of the product's geometry and attributes. High-fidelity physics-based software tools are used to predict the product model's performance to supplement or replace physical tests. Extrapolating from present experience using the universally valid laws of physics is proving to be a much better way to design innovative products. The design team can develop optimized designs instantiated as virtual prototypes, then test them to identify design flaws and make necessary design changes well before metal has been cut. In addition, changes in operational requirements and product innovations can more quickly be assessed and design changes effected. The virtual prototype paradigm can be applied at all stages of the product development process, from requirements definition to sustainment. The product model and the design analysis information can propagate as digital information through the entire product development process. Transferring product descriptions as digital information can also reduce the product development time and improve the quality of the communication of technical information. It has the additional benefit of minimizing the large number of documents that traditionally must be written and read when design and production handoffs occur between different organizations involved in the product development process.

Around 2003, Goodyear Tire implemented this paradigm, and over the course of several years, they were able to reduce their time to market by a factor of four, increase the number of new products from 10/year to 60/year, and reduce product development costs by 60 percent.[2] The Goodyear high-fidelity physics-based tools had sufficient accuracy that Goodyear ultimately dispensed with all of their physical tests except for a test of the finished product conducted concurrently with initial manufacturing. Occasionally, the final test revealed a design problem, but not often enough to negate the huge market advantage of reducing the time to market by a factor of four.[3] Many other companies have implemented this paradigm,[4] but it's generally difficult to get hard information on their successes. Virtual prototyping with physics-based prediction tools provides a competitive advantage and is considered a trade secret. The US nuclear weapons design laboratories have utilized this paradigm since the beginning of the Manhattan Project. It's not common knowledge, though, because there is no reason for them to advertise the effectiveness of physics-based computational engineering.[5]

The power of this approach was recognized early by the civil engineering community. In the 1970s, engineers used engineering applications on workstations to design buildings and complete the interior layout (electrical, plumbing, heating and air conditioning, windows and doors, structural supports, and so on). The laws of physics are captured in the standard building codes. Structural analysis with tools like NASA Structure Analysis (Nastran; see http://en.wikipedia.org/wiki/Nastran) followed. There are now multi-physics commercial tools such as MatLab (www.mathworks.com/products/matlab), Ansys (www.ansys.com), and Comsol (www.comsol.com), that run on workstations and can handle moderate-size problems that integrate several different physics effects. The microprocessor industry has used the virtual prototype paradigm since the mid-1970s when the Simulation Program with Integrated Circuit Emphasis (SPICE) code appeared.[6] Today, descendants of SPICE are used to construct and analyze models for all new integrated circuits.[7] The most ambitious multi-physics analyses require supercomputers due to the sheer number of calculations required.

At present, the computing power available for moderate- to larger-scale engineering analysis is approximately 10 to 1,000 TeraFloating Point Operations (TFLOP)/s

(Tera = $10^{12}$). It's routine to use 10 TFLOP/s or more for a few hours to a week or more to assess challenging engineering problems. The US government proposes to build an exascale computer ($10^{18}$ FLOP/s), and the most powerful computer in the world today (in China) runs at approximately 30 PetaFLOP/s (Peta = $10^{15}$).

Computing power in the 100 to 10,000 TFLOP/s range is a breakthrough for computational engineering in terms of analysis capability. With such powerful computers, engineers can use codes that are numerically accurate, include the most important physics effects, can handle large problems that span a wide spatial and temporal range (such as a complete airplane or ship), are well validated, and run sufficiently fast that the engineers can obtain reliable decision data in a timely fashion. Industry is beginning to use high-power computers, as well. Recently, General Motors (GM) opened a $130 million supercomputer facility to study vehicle crashes and minimize air drag. For GM, it's faster and cheaper to use physics-based analysis employing virtual prototypes with high-performance computers than to construct and destructively test a large number of vehicles.

## Learning from Goodyear

The Goodyear story provides a fairly complete picture of the ecosystem that is required for virtual prototyping to be effective:

1. sponsors (for example, corporate marketing, sales, and engineering leadership) who need product development decision data and are willing to pay for it;
2. subject matter experts (such as tire designers) to do the analysis and advise the decision makers;
3. high-performance computers (computing requires computers);
4. high-speed networks to connect the design engineers to the supercomputers;
5. an experimental test program to provide validation data for the software tools; and
6. physics-based software applications that can provide accurate performance predictions of the product design.

Much of the ecosystem is generic—it can be used for many different applications. However, the software applications pose the most difficult challenges to develop and support. They are generally different for each specific class of products and are costly to develop (10–15 experts for approximately 10 years).[8] For many commercial systems, commercial software tools may be adequate (for example, Ansys), so that the lead time is reduced. However, the cost of licenses should be included in the economic analysis of the value of the virtual prototyping approach.

The Goodyear story also illustrates many important advantages and challenges of virtual prototyping. Goodyear was able to dramatically improve their product-development process (as mentioned before, by a factor of four reduction in time to market, and then also a six-fold increase in the number of new products each year), but it took 10 years to build the software applications and the necessary computational ecosystem. The company only undertook the risk of adopting virtual prototyping when they were facing severe financial challenges, and had no other choice because the tried and true "design, build, test, fix" process wasn't fast enough to develop new products fast enough to keep the company competitive.

Another lesson is that Goodyear initially only changed its design process. It kept the "design, build, test, fix" product-development process, including all the physical tests. The virtual prototype designs (tested with internally developed software tools that were developed with help from the Sandia National Laboratory) passed the tests so that redesign and rework and the associated time and cost growth was much less. As the process matured, the physical tests were recognized to be redundant and were dropped by the product development organization since the virtual testing caught the major design flaws early when they could be easily fixed. After a few years, Goodyear went into production and physical testing at the same time. Occasionally, the test turned up a problem. Goodyear analyzed the test results and fixed the code. They continued relying on virtual prototype designs because the productivity gains from the use of virtual prototypes far exceeded the costs of an occasional hiccup in the product development process.

Today, the US faces intense international economic and military competition from our allies and foes. Although US industry is still competitive and remains the leader in product innovation, its lead over the rest of world could vanish in a few years. On the military side, the US military advantage is due to its superior military technology and its large military budgets. However, the cost of new weapon systems and the time to develop them are growing dramatically. The plethora of recent news articles on the Joint Strike Fighter (JSF) and the Littoral Combat Ship (LCS) demonstrate the product-development challenges facing the US Department of Defense (DoD). The Department of Defense is beginning to experiment with the use of virtual prototyping to reduce acquisition time, cost, and risks. The DoD High-Performance Computing Modernization Program CREATE program (www.hpc.mil) is having very positive results with virtual prototyping. The use of virtual prototyping by private industry is rapidly growing. However, our foreign competitors are also beginning to adopt computational engineering. This offers them the ability to leapfrog over organizations that are relying on the traditional "design, build, physical test, fix" paradigm. Virtual prototypes offer the US great potential for keeping its competitive edge, but only if the US aggressively adopts their use. If it doesn't, it runs the risk of being overtaken and passed in the global innovation race. ■

## References


1. A. Kossiakoff and W. Sweet, *Systems Engineering Principles and Practice*," John Wiley and Sons, 2003.
2. L.K. Miller, "Simulation-Based Engineering for Industrial Competitive Advantage," *Computing in Science & Eng.*, vol. 12, no. 3, 2003, pp. 14–21.
3. Goodyear Tire, *Goodyear 2009 Ann. Report*, investor report, 2009; http://investor.goodyear.com/annuals.cfm.
4. Council on Competitiveness, *Council on Competitiveness: HPC Success Stories*, 2010; www.compete.org/about-us/initiatives/hpc/success%20stories.
5. S. Francis, *Warhead Politics, Livermore and the Competitive System of Nuclear Weapon Design*, Dept. of Political Science, Massachusetts Inst. of Technology, 1995.
6. L.W. Nagel and D.O. Pederson, *SPICE (Simulation Program with Integrated Circuit Emphasis*, memorandum, Univ. of California, Berkeley, Electronics Research Laboratory, 1973.
7. R.P. Colwell, *The Pentium Chronicles: The People, Passion, and Politics Behind Intel's Landmark Chips*, Wiley/IEEE Computer Society, 2005.
8. R. Kendall et al., *Case Study of the Hawk Code Project*, Los Alamos Nat'l Lab., 2005; http://library.lanl.gov/cgi-bin/getfile?LA-UR-05-9011.pdf.



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