SEI SERIES IN SOFTWARE ENGINEERING

Creating and Using Virtual Prototyping Software

Principles and Practices

Douglass E. Post

Richard P. Kendall

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Chapter 4

Examples of Virtual Prototyping Software (Tools)

This chapter describes some examples of the software tools that play a role in creating virtual prototypes. Generally, one tool cannot do everything.

4.0 Introduction

The preceding chapters describe the value of using digital prototypes or surrogates for product development and scientific research. They also highlight the key roles that computing, in general, and software, in particular, can play in modern product design and science. This chapter provides some examples of this software and illustrates their role in a product development workflow. Because of the paucity of examples in print of product development workflows outside of canonical ones such as ISO/IEC 15288 and the Systems Engineering Life Cycle workflow model (product development workflows are usually considered proprietary), this chapter focuses on examples from the CREATE program, which supports the DoD 5000 Acquisition lifecycle workflow (www.acquisition.gov).

Virtual prototypes were defined in this book's preface as mathematical representations of manufactured objects or a physical system captured in digital form. The key advantage of these digital incarnations (often referred to as *digital models*, although software developers reserve this term for digital product models) is that they can predict the behavior of an object or system before it even exists—or, in the case of natural systems, without ever having direct contact with the object or system or exerting any direct control over it.

Even before computers, the concept of a virtual prototype has a long history. The efforts of ancient peoples such as the Babylonians (circa the 7th and 8th centuries BCE) to use models and mathematics to predict astronomical events such as eclipses and planetary motion (specifically, their development of an empirical model to predict the behavior of the stars, the moon, the planets, and other astronomical objects) is an example of a virtual prototype (Aaboe 1958). Similar to modern digital virtual prototypes, the Babylonians' model was validated by observations of the motion of these celestial objects. One of the most familiar ancient examples of a virtual prototype is the geocentric model of the heavens developed by the Greek astronomer Claudius Ptolemaeus in Alexandria, Egypt (circa 100–170 CE). The model is described in *The Almagest* (Toomer 1984). In the Ptolemaic model, the spherical Earth is motionless; the fixed stars, planets, moon, and sun revolve around Earth in various complicated orbits (epicycles), as depicted in Figure 4.1.

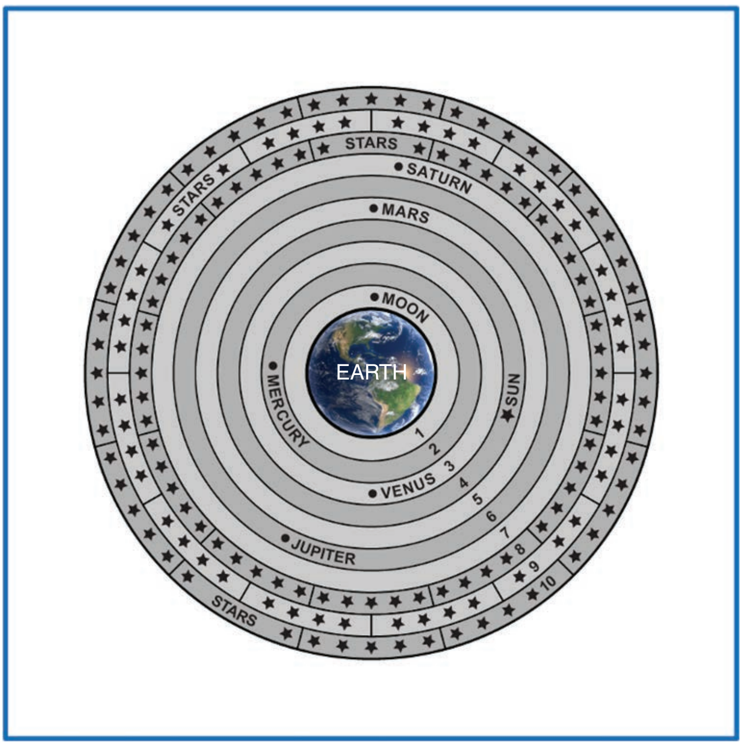

Figure 4.1 *Ptolemy's model of the planets*

(Courtesy Software Engineering Institute)

Today the term *virtual prototype* refers to a digital representation of a real physical object—*virtual* has become synonymous with *digital*, in this context. This can be a complex manufactured or assembled product (such as an automobile, an airplane, or a golf club) or a natural object (such as a river; a watershed; a weather system that combines the ocean, atmosphere, land, and sun; or an astrophysical system). It can also be a biological system (such as a virus, a plant or animal, the human cardiovascular systems, or neural systems). A virtual prototype can even be a model of the behavior of groups of people (such as sports teams, groups of voters, or military units engaged in combat). The concept of a digital prototype can be realized for any physical system that can be described by a mathematical model (Post 2014).

As emphasized in Chapter 1, "The Power of Physics-Based Software for Engineering and Scientific Research," the digitally based research and product development paradigm can supplement and sometimes even replace the construction and testing of physical prototypes for product development or physical experiments for scientific research. Digital surrogates can greatly reduce the cost and time required to design and manufacture a complex product or complete a scientific research project. Computing is the enabling technology, so the use of virtual prototypes requires a computing ecosystem (described in Chapter 2, "The Computing Ecosystem"), consisting of computers, networks, data and data storage, users, and software applications (tools).

4.1 The Research Heritage

In our experience, most of the components of software destined to support virtual product design and analysis or scientific research trace their roots back to research codes that were generally intended for use only by their developers. This observation does not apply to research codes such as FLASH (Fryxell 2000) and GAMESS (Gordon 2020), which were developed for community use from the beginning. However, it does apply to most of the CREATE tools and many commercial engineering software products. In many cases, the foundations for the multiphysics CREATE software were single-physics research codes developed by DoD research laboratories or federal agencies such as NASA and the Department of Energy. NASTRAN (Mule 1968) and LS-DYNA (Hallquist 1976) are commercial examples of engineering codes that have their origins in research organizations. A key challenge facing product design and scientific research communities is bridging the gap between these research precursors and practical, usable design and research tools that deliver reproducible results (Barba 2016). Table 4.1 offers some insight into why.

Table 4.1 *Research-Only vs. Production-Level Engineering Design and Scientific Research Software*

	Typical Scientific Research Software (Precursors)	Mature Engineering Design and Scientific Research Software
Purpose of software	To advance research, typically through publication	To facilitate product design or scientific research
Customer communities	Primarily other researchers	Design engineers and research scientists
Deliverable	Executables primarily used by the developer, with few or no other users	Production quality software with user support for users who are not developers
Adoption of software engineering practices and processes	Minimal to nonexistent	Recognized as required for usability, reliability, reproducibility, and other "ilities"
Emphasis on software quality	Not important—often no reuse of the software is expected	High—must meet or exceed commercial software standards
Emphasis on documentation	Low—often the developers are the only users	High—documentation is augmented with tutorials, training, Wikis, videos
Development team size	Small—sometimes only a single researcher	Typically done by small (<10) teams or groups of small teams
Team composition	Primarily researchers	Multidisciplinary teams, subject matter experts, computer scientists, software engineers, database experts, and others
Emphasis on accuracy	High	Matched to the stage of design or research process
User support	Little or no organized support for users—at best, informal support by developers; few or no bug fixes or new features for external users	Dedicated user support, bug fixes, feature enhancements

Whereas a small team or even an individual might take only a few years to develop research code, a multidisciplinary, close-knit team might take years or even decades to produce a multiphysics, high-performance computing design and analysis tool that can be used effectively by an external community of design engineers, analysts, or scientific researchers. For example, the CREATE code teams spent their first 5 years developing the basic functionality needed to assist in the design and analysis of the DoD weapons systems that they were intended to support. The FLASH astrophysics code has been through three generations of its software in 2 decades (Carver 2017).

4.2 A Brief Description of the Tool Chain That Enables Virtual Prototyping for Products

Typically, virtual prototypes are not the output of a single software tool. Robust product designs are created by a software tool chain linking the following components:

- Meshing and geometry tools to create a product model
- Conceptual design tools that allow exploration of the design tradespace
- Performance analysis tools that support detailed design and virtual prototype testing
- Operational support tools that support product manufacturing, maintenance, and upgrades

Beyond the design stage, CAD and CAM manufacturing tools also come into play. Table 4.2 provides an overview of the tools typically found in the tool chain.

Table 4.2 *Virtual Prototyping Software Tool Chain: An Overview*

Product Design Tools	Task
Requirements synthesis support tools	Requirements gathering and definition
Meshing and geometry generation tools	Development of 3-D product models for conceptual design and design analysis
Conceptual design generation tools	Generation of 3-D digital product models (digital design options)

Product Design Tools	Task
Conceptual design analysis tools, operational performance tools	Support performance assessments of conceptual design options
Tradespace analysis tools	Evaluation of tradespace candidates to select the best design options
High-fidelity, physics-based design and analysis tools	Detailed design analysis and virtual tests of the design
Manufacturability analysis tools	Design for manufacturability
High-fidelity, physics-based design and analysis tools and other tools as needed	Support for product production (production and manufacture) with forensics, to identify design defects and then identify and repair them as they are uncovered
Product deployment and sustainment tools	Support for product deployment and final physical testing, together with performance analysis of upgrades
Software deployment and sustainment tools	Support for the continued development and deployment of software, user support, and training

Often virtual product design tools can support more than one of these tasks. Versions of many product design tools are available from independent software vendors. Commercial examples include ANSYS, COMSOL, MatLab, NASTRAN, Cobalt, and LS-Dyna. Open-source software engineering and scientific tools, such as OpenFOAM, are also available. Many can be discovered on the web (SourceForge Science and Engineering 2021). Government agencies have developed product design tools or components of them. Examples include NASA (OverFlow) and the Department of Energy Laboratories, including Sandia National Laboratories (Sierra Mechanics Suite, LAMMPS, and Zapotec), Lawrence Livermore National Laboratory (ALE-3D), Los Alamos National Laboratory (MCNP), and Oak Ridge National Laboratory (CASL). DoD laboratories such as the Air Force Research Laboratory have developed tools such as AVUS. Commercial entities including Autodesk, Siemens, Dassault Aviation, and PLM Software market product design tool sets. Finally, corporations such as Boeing, Goodyear, Ford, and many others have developed proprietary digital engineering tool sets that facilitate parts of the virtual prototyping paradigm. Grand View Research forecasts global growth in the market for virtual prototyping tools at a compound annual rate of 19.4% from 2018 through 2025 (GrandViewResearch 2018). Illustrative examples provided in the following sections are taken from the CREATE tool chain.