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REFLECTIONS

The need for a science of engineering informatics

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1. INTRODUCTION

> Plus ça change, plus c'est la même chose.
>
> Alphonse Karr

Why has integration and interoperability of design and manufacturing knowledge proven so difficult? There is a common puzzle that appears in your Sunday newspaper or *The New Yorker* magazine. Match the following quotations with their source, all of which have been excerpted from reports from either the National Science Foundation or the National Academies:

(1) . . . Although . . . tools have come a long way . . . the major hurdles today is [sic] the lack of interoperability between dissimilar tools . . . cumbersome model preparation . . .	(a) *Visionary Manufacturing Challenges for 2020*, National Research Council, 1998, p. 25
(2) The structuring of design information and data integration are critical requirements for data sharing between designers separated physically and in time, as well as between companies, vendors and customers. Standards do not yet exist for modeling many engineering and organizational parameters that are essential for design specification and analysis, nor are there standards for structuring rational for decisions and design procedures used.	(b) Improving Engineering Design: Designing for Competitive Advantage, Manufacturing Studies Board, National Research Council, 1991, p. 55
(3) Data communication in a heterogeneous system, validation, and consistency of data, representation of textual and geometrical data, . . . , analytical models of manufacturing processes are all risky areas of research, requiring multiyear, cooperative efforts. Solutions to these problems are needed . . .	(c) *Information Technology for Manufacturing: A Research Agenda*, Manufacturing Studies Board, National Research Council, 1995, p. 81
(4) Interdisciplinary collaborations will be especially important for implementing comprehensive processes that can integrate the design of mechanical systems with the design of electrical systems and software. Successful collaborations, however, will first require overcoming incompatibilities between emerging technologies and the existing technological infrastructure and organizational cultures.	(d) *ED2030: A Strategic Plan for Engineering Design*, National Science Foundation, 2004, p. 10
(5) For many organizations, a fundamental change in the engineering culture will be necessary to take advantage of breakthroughs in advanced computing, human–machine interactions, virtual reality, computational intelligence, and knowledge-based engineering . . .	(e) *Educating the Engineer of 2020: Adapting Engineering Education to the New Century*, National Academy of Engineering, National Academies Press, 2005, p. 10
(6) Researchers and faculty members desiring to work on interdisciplinary research, education, and training projects should immerse themselves in the languages, cultures, and knowledge of their collaborators . . .	(f) *National Collaboratories: Applying Information Technology for Scientific Research*, Computer Science and Telecommunications Board, National Research Council, National Academy Press, 1993, p. 56

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(7) The need is for a formalism that supports representation of designs at the multiple levels of abstraction and detail appropriate to different stages of the design process.	(g) *Research Opportunities in Engineering Design*, National Science Foundation Strategic Planning Workshop, Final Report, April 1996, p. 20
(8) Information technology is often adapted for manufacturing operations by people who are knowledgeable in information technology but not business operations. Consequently, investments in information technology in manufacturing environments have not resulted in the anticipated increases in productivity. . . . Many manufacturers feel that the current system of education . . . does not prepare employees for high-technology jobs. For example, universities have been increasingly challenged to train students in the use of advanced information technology to address business basics, including financial analysis and human factors. A truly interdisciplinary curriculum that considers information technology in a global context would make information systems much more useful to manufacturing enterprises.	(h) *Advanced Engineering Environments: Achieving the Vision—Phase 1*, Aeronautics and Space Engineering Board, National Research Council, National Academy of Engineering, 1999, p. 3
(9) . . . contemporary challenges . . . increasingly require a systems perspective. This drives the growing need to pursue collaboration with multidisciplinary teams of technical experts.	(i) *Computer Integration of Engineering Design and Production*, National Research Council, Manufacturing Studies Board, National Academy Press, 1984, p. 5
(10) . . . the design environment will have to handle data legacy issues, such as converting data from one CAD system to another and preserving old data for decades or more so that they can still be read, edited, and processed. Today, such data are either lost, kept on paper, or accessed in a limited way by old hardware kept on hand for the purpose.	(j) *Improving Engineering Design: Designing for Competitive Advantage*, Manufacturing Studies Board, National Research Council, 1991, p. 54
(11) A design knowledge base more generally and completely accessible to all engineering designers would be tremendously powerful. For this vision to be realized, existing knowledge must be organized and, where possible, generalized. Once this is done, the knowledge might be made available to designers via CAD systems or computer networks.	(k) *Facilitating Interdisciplinary Research*, National Academy of Sciences/National Academy of Engineering and Institute of Medicine, National Academies Press, 2005, p. 4
(12) . . . common information-related problems that have led . . . to ad hoc and idiosyncratic solutions. (1) Data sharing. The capability for scientists in different locations working on the same project to quickly and easily obtain access to data, both within and across databases. (2) Software sharing. The capability for scientists in different locations to conveniently share software that supports data analysis, visualization, and modeling.	(l) *Design in the New Millennium: Advanced Engineering Environments—Phase 2*, Aeronautics and Space Engineering Board, National Research Council, National Academy of Engineering, 2000, p. 1

An observation one might easily make is that it is largely irrelevant as to which quote gets matched to which report or document. By and large, all of the quotations drive at the same problems of the role of information in design and manufacturing and how information can be acquired, integrated, and harnessed. Considering the dates of publication, one can see that the fundamental issues in design and manufacturing informatics have largely remained the same over the past 30 years. The vocabulary of scientific discourse has evolved and changed. Technology and tools have also changed. These changes, however, have not vanquished the core scientific challenges.

In some ways, we are like repeat offenders. Each generation of technology creates an opportunity for us (government, industry, and academia) to return to the scene of the crime and void our parole. However, rather than an indictment, I see this pattern as revealing a much deeper set of issues. For instance, although there have been great strides made by academic and commercial entities in the past decades, it would seem from the themes of these reports that the fundamental problems of information integration remain the same. Why the apparent lack of fundamental progress in areas of information integration? Let us consider several other computing disciplines in which evidence of fundamental progress is self-evident.

1.1. Computer networking

Shannon's fundamental laws have allowed scientists and engineers to predict the theoretical maximum capacity for communication channels in various media. This theoretical limit provides a continuous objective to aim for in the creation of systems, hardware, and algorithms for networked communication and information coding. What continually surprises researchers is their repeated ability to achieve results increasingly close to these theoretical limits for mediums such as fiber optic communications. Spurred on by these successes, networking and communications researchers now are tackling other, more challenging mediums such as free-space optical, ad hoc networks, and wireless (i.e., 802.11, etc.) networks in an attempt to absolutely maximize the capacity of these channels. We all experience these successes (i.e., our telecommunications costs for basic global telephony heads toward ε cents/minute thanks to Voice over IP technologies).

1.2. Computer graphics

CAD/CAM applications gave birth to the entire field of computer graphics. Ironically, however, the graphics community has vastly eclipsed that of "design and manufacturing" in its ability set metrics for itself and achieve them. The major transformation of the graphics community in the past 15 to 20 years has been the clear focus on the shared objective of creating completely convincing artificial realities. These objectives are driven by the film and video gaming industries and supported now by annual research and development budgets coming out of industrial film and gaming companies. These budgets are on the scale of the production budgets for major motion pictures. Further, the "reality" of these realities can be easily assessed, completely without complex metrics, by the average theatergoer who thrills at being transported into the midst of a massive battle for the future of humanity on the plains of Minis Tirith.

1.3. Computer systems

Computer systems comprise digital storage systems, VLSI design, and the creation of devices that continue to quadratically improve in their computational power. In each of these subareas, there are immensely challenging physical laws that constrict and restrain what engineers can achieve in their mediums. However, engineering achievements in these areas are the results of their continuing to find pathways forward that produce quantitatively impressive improvements. We get to tangibly experience these accomplishments with each new generation of computing devices and from the iPod that can hold all the music that I would ever want to hear.

An important observation regarding the success in computer systems engineering is that results in these areas also stem from the ability of the R&D communities in these areas to agree on standards (i.e., MOSIS) and accept constraints on the design and manufacturing activities. Although the idea of a "mechanical MOSIS" has been often mentioned and attempted, it's not clear that the design/manufacturing space for electromechanical systems can be decomposed and decoupled in any reasonable way that could produce the kind of economies of scale and success that has been found in these other areas.

2. REASONS FOR PROBLEMS

What may the reasons be for the continuity and persistence of these problems of information integration in design and manufacturing? I offer several ideas.

2.1. The lack of fundamental laws

The laws of information theory are universal, providing a means of measurement of communications capacity and codings. Further, the theory itself reveals the "bar" of how well one could ever expect to do. Research efforts then have been directed toward moving our fielded systems ever closer to that bar.

Although there has, in recent years, been several different explorations of different "theories of design and manufacturing," in particular the use of decision and game theory, nothing has yet emerged that can provide such objectively quantifiable objectives for information integration as information theory has provided for communications. Fundamental laws for information and knowledge integration are likely to look different than those that exist today in "traditional" research communities.

2.2. Lack of a single stakeholder

Certainly the United States government (i.e., Department of Defense, NASA, etc.) represents a vast stakeholder that can place its investments into areas and demand results. Place a human on the moon? Check. Stealth aircraft? Check. For design and manufacturing knowledge integration there are many stakeholders, some of which would rather see knowledge remain in proprietary formats and systems. Even the large industrial players have multiple stakeholders within their ranks. Hence, although great feats of individual integration are routinely achieved (e.g., 777), it is unclear which of these results transfer beyond the system at hand and the company that paid for it. It remains difficult to quantify payoff and economic benefits of information interoperability, something that should be seen as a public good.

2.3. Breadth (vs. narrowness) of objectives

In networking, the objective has often been to maximize bandwidth; for computer storage, the measure is bit density and so forth. Recent work on networking focuses on maximization or optimization of other quantitative measures such as power consumption, spectrum allocation, or network availability. Taken independently, each of these objectives is much narrower than the issues posed by engineering informatics. Certainly the interdisciplinary problem space that must be optimized against is much wider.

2.4. Lack of metrics

The other fields all have metrics universally accepted by their respective research communities. The metrics may be quantitative or qualitative, but they are generally interpreted the same way by all players. For information integration problems, there are no such universal metrics.

3. A UNIQUE SITUATION?

Is this situation unique in science and engineering? Engineering design and manufacturing is certainly not the only discipline that suffers in this way. Interdisciplinary problem spaces are increasingly at the forefront of our national challenges.

3.1. Computer security and information assurance

It has long been realized that information security needs to be viewed at a holistic, system level. I can have the greatest cryptography and firewalls in the world, but if I leave sensitive materials in my wastebasket the janitor can take them sell them to my competitor.

Security research, much like that in engineering design and manufacturing, runs a very wide gamut. For security, this means it spans from those that study human and organizational behavior to those that study access control, stegonography (hiding a secret message inside other messages or images), and key management.

3.2. "System of systems" design

The United States Department of Defense, Federal Aviation Administration, and others face the new problem of having to design products that are a "system of systems." Such products are composed of many interacting entities: design objectives related to their collective output and behavior. For example, designing a system to support a heterogeneous team of human and robotic first responders requires not just designing the robots. For example, given that all system components affect all others, the designer of the robotic actuators will need to have access to knowledge about the RF properties of the materials employed, as well as how his actuators enable (or disable) the ability of the robot to interoperate with the other devices and humans in the system.

4. MOVING FORWARD

How to move forward? I am left with little choice but to invoke the vision of the landmark paper "As We May Think" by Vanaver Bush (1945). Bush, based on his experiences as the Director of the Office of Scientific Research and Development during World War II, describes a fantastic integration of information to support the mission of scientific inquiry for the greater national and human good. In the past 15 years, his fantastical device, the "MEMEX," has found its incarnation in the Internet and currently emerging information and computing technologies. This Web-enabled MEMEX-like knowledge integration has revolutionized the traditional *process* of science and engineering. What remains is the full transformation of science and engineering itself into information-centric enterprise.

Results will not be achieved by thin mixing of the disciplines. For example, decision theorists dabbling in engineering design (or vice versa) is not the recipe for a transformation of either discipline. The reason for this has been extensively argued by historians of science such as Kuhn (1996) and others: simply applying the tricks and tools of one discipline to the puzzles of another does not lead to revolutionary new ways of thinking. It is only by a true paradigm shift that the problems can be viewed in their true nature and wholly new languages, formulations, and scientific techniques emerge to reposition our frame of reference. I believe that the proper name for this discipline in the context of design and manufacturing is "engineering informatics."

One can easily point to the information age's frustrations regarding knowledge interoperability and systems integration and feel a bit like a frustrated medieval astronomer trying to figure out why the planets, which certainly must have circular orbits, seem to make such bizarre movements in the night sky. These problems of information integration and interoperability linger, reminding us that our bag of tricks, tools, and theories are not yet adequate to describe the phenomena we see in a fundamentally complete, and transformative, manner.

REFERENCES

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Kuhn, T.S. (1996). *The Structure of Scientific Revolutions*, 3rd ed. Chicago: University of Chicago Press.

ANSWERS TO TEXT QUIZ

(1) d, (2) g, (3) i, (4) l, (5) h, (6) k, (7) j, (8) a, (9) e, (10) c, (11) b, (12) f.