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Title: THE IMPACT OF TECHNOLOGY ON THE SCIENTIFIC METHOD

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The Impact of Technology on the Scientific Method

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"Doing Science" is more complex today than ever. Yet as we move towards addressing more and more difficult problems, and realize the necessity to address them in a multi-disciplinary fashion, efforts are complicated by the stovepiping of disciplines and individuals' expertise, and by the fact that our established scientific methods do not lend themselves well to many forms of multi-disciplinary or team science. By "stovepiping," we mean that many scientists today are only able to keep current on a very narrow slice of disciplinary expertise. Due to the increase in the number of journals and amount of research being conducted, it is getting harder and harder to be good at what you do and have a general perspective on your own discipline, let alone science as a whole. And the scientific method we have traditionally relied upon was developed centuries ago so that lone scientists could convince other lone scientists that their physical experiments were conducted "objectively." As part of this ritual of objectivity, experiments were simplified to the point that only one thing was being considered and one answer produced. Today, we must often rely upon complex computer modeling and symbolic experimentation because physical experimentation is impractical or impossible, we must integrate types of information that would once have been dismissed as subjective, and we often must work in diverse teams to address complicated, multi-faceted, ongoing problems and produce equally robust "answers." To address the demands of modern multi-disciplinary science, we are eager to build upon the foundation of the scientific method, seeking enhancements to the scientific process both by noticing the changes that have occurred in scientific practices and by pushing to develop methods that better fit the task environments we work in.

The traditional scientific method can be represented as:

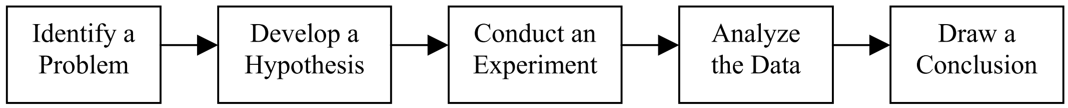

Figure 1. The Scientific Method

As suggested above, this method was developed to isolate and minimize variables, to facilitate simple description of procedures for far flung colleagues, and to follow the principles of logic popular during the scientific revolution. One of the key features of this model is its linearity—once the process starts it needs to proceed to its conclusion and produce a product in order to be seen as successful. But today, there is the ability and need to conduct science in a way that accounts for more complexity. One way of addressing complexity is by incorporating cutting edge mathematical and statistical methodologies. Or perhaps in some manner it is the other way around: that the utilization of modern mathematics and statistics, in synergy with modern science, is creating an exigency for more complex considerations. Mathematics and statistics have long been a part of the evolution of the scientific process.

Copernicus was the first to successfully unite mathematics and science. Before Copernicus, mathematics was seen as an instrumentalist activity, dealing with abstract constructs that had no relation to real world phenomena (Henry 11). His 1543 *De Revolutionibus Orbium Caelestium* (which was actually based more on calculations than observations) revolutionized the practice of science, as did later works by Galileo, des Cartes, and Newton that further established the value of the mathematical approach to understanding nature (Henry 18). Historian John Henry writes,

> Mathematical practitioners . . . became important contributors to the new trend towards experimentalism. For one of the characterizing features of the

> Scientific Revolution is the replacement of self-evident 'experience' which formed the basis of scholastic natural philosophy with a notion of knowledge demonstrated by experiments specifically designed for the purpose. Like a mathematical proof, the end result of the experiment might well be knowledge which is counter-intuitive. (24)

Additionally, these early mathematical physicists were among the first to incorporate instruments into their research, establishing another foundational component of modern experimental science.

Statistical and probabilistic theory likewise coalesced in the 1600's. Its lineage draws from two areas: (1) observations of, and the desire to predict outcomes of, games of chance; and (2) assessments of degrees of certainty (or in today's language uncertainty) in judicial proceedings, i.e., how likely is it that Mr. Jones stole the pig (See Hacking and Daston.)? Scientists were interested in these new methodologies that allowed them to make calculations and draw conclusions about repeated observations and populations, especially given their new beliefs that the universe behaved according to uniform laws and that future phenomena could be predicted based on assessments of statistical and probabilistic calculations.

In terms of technology, standard scientific progress has followed a specific process over the centuries (See Figure 2.). New ideas/theories or new questions/problems lead researchers to develop new methodologies in order to address these issues. These methodologies hopefully lead to results that provide answers and proof that lead to tougher questions and the possibility of starting the whole process over again. New technology can emerge from this process either as a bi-product (a means) of methodological/tool development or as a result/product (an end). This can be seen in the story of Copernicus, who had issues with Ptolemaic cosmology. He developed realist mathematical methodologies to arrive at a set of results, which then allowed him and later researchers to ask tougher questions and develop new theories.

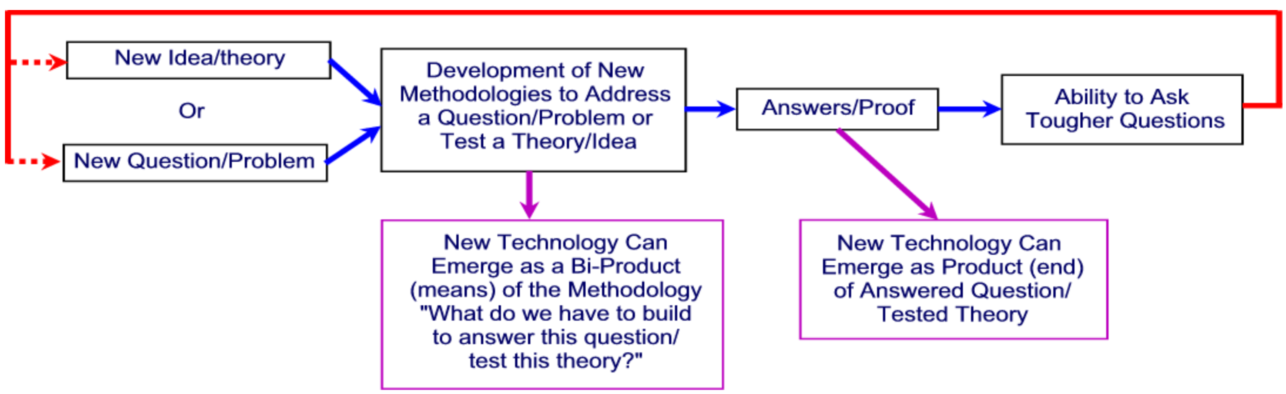

Figure 2. The Scientific Process

But because we are looking at increasingly complex problems, science may need more than the method of Figure 1 and the process of Figure 2. Science may need to build on the foundation of Figure 1 to develop a new process to address new types of problems or to capture how our current way of solving problems is different. In fact, complex multi-disciplinary science often seems to be working in the opposite direction from that indicated in Figure 2. In our environment at Los Alamos National Laboratory (LANL), for example, technology often drives the process (See Figure 3.). Technology developed at, or made available to, LANL (e.g., incredibly fast super computers or the Metropolis algorithm) creates an expectation of being able to answer tougher questions. By design, the technology comes to science in search of questions. Once the questions are posed, science must search for methodologies to answer those questions. And frequently, scientists find themselves trying to figure out the theoretical meaning and importance of the work they've done.

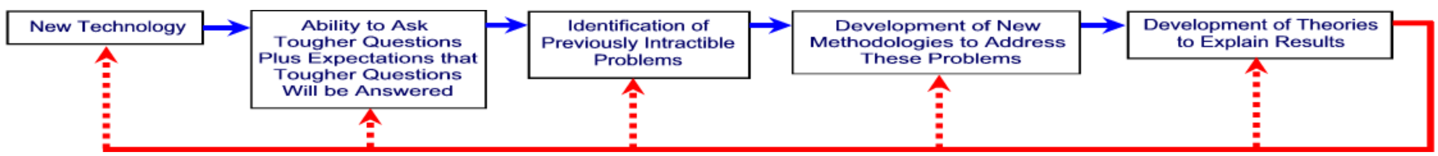

Figure 3. An Alternate View of the Scientific Process.

This process depicted in Figure 3 is less linear and more recursive than traditional representations of the scientific method in that the products of the process can plug in at (update) any stage in the diagram. The products are not just an opportunity to start the whole process over again. This breakdown in lockstep linearity is one of the changes we see in the process of the scientific method. As concrete example, consider Science Based Stockpile Stewardship (SBSS) at LANL, and the history that has brought us to this problem. From its earliest days, LANL has had a prominent role in the development and evaluation of the U.S. nuclear weapons stockpile, but the end of the Cold War brought significant changes to how this mission could be carried out. There have been significant reductions in the number of weapons, leading to a smaller, "enduring" stockpile. The United States is no longer manufacturing new-design weapons, and it is consolidating facilities across the nuclear weapons complex. In 1992, the United States declared a moratorium on underground nuclear testing; in 1995, the moratorium was extended and President Clinton decided to pursue a "zero yield" Comprehensive Test Ban Treaty. However, the basic mission remains unchanged: LANL must evaluate their weapons in the aging nuclear stockpile and certify their safety, reliability, and performance even though the kind of data that has traditionally been used for this evaluation is no longer available.

To complete this mission a two-pronged approach of experiments and computational modeling was adopted. The experimental approach is exemplified by the Dual-Axis Radiography for Hydrotesting (DAHRT); the computational modeling effort by the Accelerated Strategic Computing Initiative (ASCI). At its core, however, this approach is the same as the one that has been pursued since the earliest days of the Lab. Symbolic experiments have often been required when physical experiments proved too difficult or dangerous. To do these symbolic experiments Los Alamos implemented the first "computers" during World War II; the computers were people, mostly the wives of scientists, sitting in rows with adding machines doing sequential calculations to model complex physical processes. At a fundamental level, the new experimental and computer technologies have not been developed to address SBSS; rather a "zero yield" policy could be negotiated and implemented because advances in computer technology made it seem feasible that the sophisticated modeling could be done to realize SBSS. In short, the promise of the technology drove the policy. It created an expectation that certain tough questions could be answered with adequate justification.

Alongside the efforts at experimentation and modeling, statisticians have been working to integrate historical data and to quantify the vast resources of expertise at LANL in such a way as to facilitate their inclusion through Bayesian statistical methods (Malakoff). The challenge is to integrate data, information, and knowledge from the experiments, computational models, past tests, sub-system tests, and the expert judgement of subject-matter experts to provide a rigorous, quantitative assessment, with associated uncertainties, of the safety, reliability, and performance of the stockpile.

The complexities of big science problems such as SBSS can quickly become overwhelming, and without careful attention to the whole picture or purpose, the accomplishments of individual scientists (following the traditional scientific method) can become lost and detached. As some of the key information integrators, we have recently gone back to the "beginning" and reformulated our basic understanding of how decision-making under uncertainty works and what its relationship seems to be to the traditional scientific method. This has led us to an understanding that is captured in Figure 4.

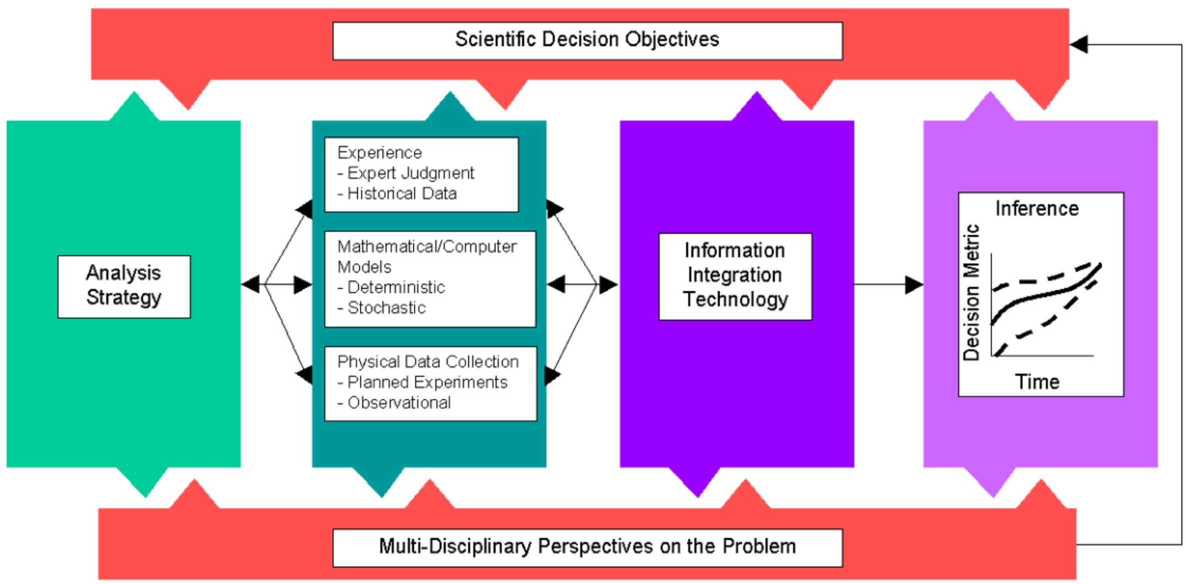

Figure 4. Time-Dependent Decision Making Framework

Recognizing that the overall problem/goal is "decision making" and not modeling is a key point to emphasize here. LANL is clearly in a peculiar position of doing complex science that is closely tied to national policy decisions. However, all applied science feeds into decision making scenarios: How much CO_2 is too much to be coming out of a tail pipe or smoke stack? Does this micro chip design offer substantial improvement over its predecessor? Is this vaccine safe and effective?

We refer to Figure 4 as a "Time Dependent Decision Making Framework" because we know the type of data we are concerned with will change over time and we need to be able to update that information within the framework and then update the structure of the components as need be. So, far from being a static and linear method where variables are purposely minimized, this diagram represents a dynamic and recursive space where each box has potential to produce new information that can update any other box, resulting in other updates. The goal is that at any slice in time, the best possible information is available to guide decision making.

The first piece of decision-making is to define the decision objectives: What is it that we are trying to understand and decide? The second piece is to understand the perspective that the multi-disciplinary team members (or multiple communities of practice) may have on the problem. Within SBSS, the team members and the communities they represent understand the problem in different ways: physicists are interested in the physical processes, weapons designers are concerned with harnessing physics, materials scientists think about explosives and aging materials, engineers are interested in parts, statisticians are thinking about uncertainty quantification, computer scientists contemplate complex codes, and politicians are of course concerned with matters of policy. The third piece of decision-making is the analysis strategy. Before any information is collected, it must be determined how this information will be analyzed and integrated, and how the results should bring better resolution to the decision objectives. These determinations should drive the requirements regarding what data to collect. The fourth piece is data, information, and knowledge. Today, every decision incorporates more than just "data" in its narrow sense. It also incorporates information and knowledge to do such things as understand the problem, structure the representations, find data sources, and select appropriate models. Even "data" in its narrower sense can include such things as opinions elicited from experts and outputs from computer codes. The fifth piece of decision-making is the "information integration" technology, or the statistical, mathematically tractable, methodologies needed to tie all of the decision objectives, community representations, and data together. If these technologies are effective, they lead to the sixth piece of decision-making, which is inference (with associated uncertainties) about the decision objectives of interest. This inference must be dynamic, or performed over time, as the information about the problem changes.

Implications

This article travels through several representations of scientific method and scientific processes. Much like in Figure 3, where scientists get to the last step and try to make sense of their experience and knowledge gained, we have noticed that the way we have always been taught to understand the scientific method doesn't seem to explain the work we currently do. Figure 4 is how we have tried to make sense of, and give structure to, what we believe the process is today. Does this richer, more dynamic, representation of the scientific process have implications beyond our personal experiences? We believe it does and think it could help researchers to understand the connections between science and decision making in a way that informs each. We need to understand how the contributions scientists make support decision making at all levels and how scientific methods fit into those broader contexts. From a team science perspective, Figure 4 emphasizes the integration of multi-disciplinary perspectives instead of forcing everyone into a common representation, thus making it possible to draw data and information from a broader spectrum of expertise without losing a little of each community's knowledge in the translation. Likewise, applying Figure 4 to a more loosely organized effort like the international search for an AIDS vaccine can become a map that allows each participant to locate their place in the big picture, to understand how their efforts are contributing to the whole and even to recognize what parts are not being addressed. Finally, if we are right that the rules are shifting some in the game of science, all of us who play that game had better pay attention. The scientific method may still be firm beneath our feet, but our understanding of how it functions should be as dynamic as our ongoing search for understanding in the universe.

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