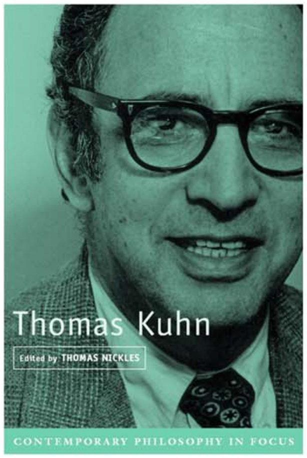
Kuhn, Galileo, Casimir:
Insights into the relationship between S&T



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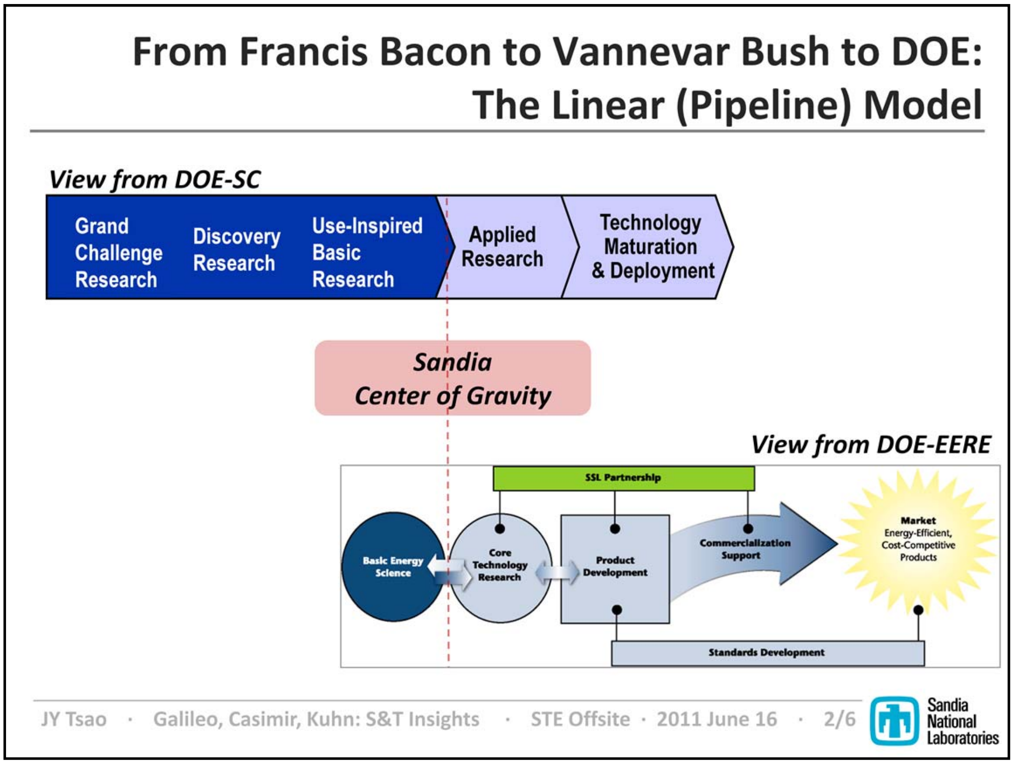
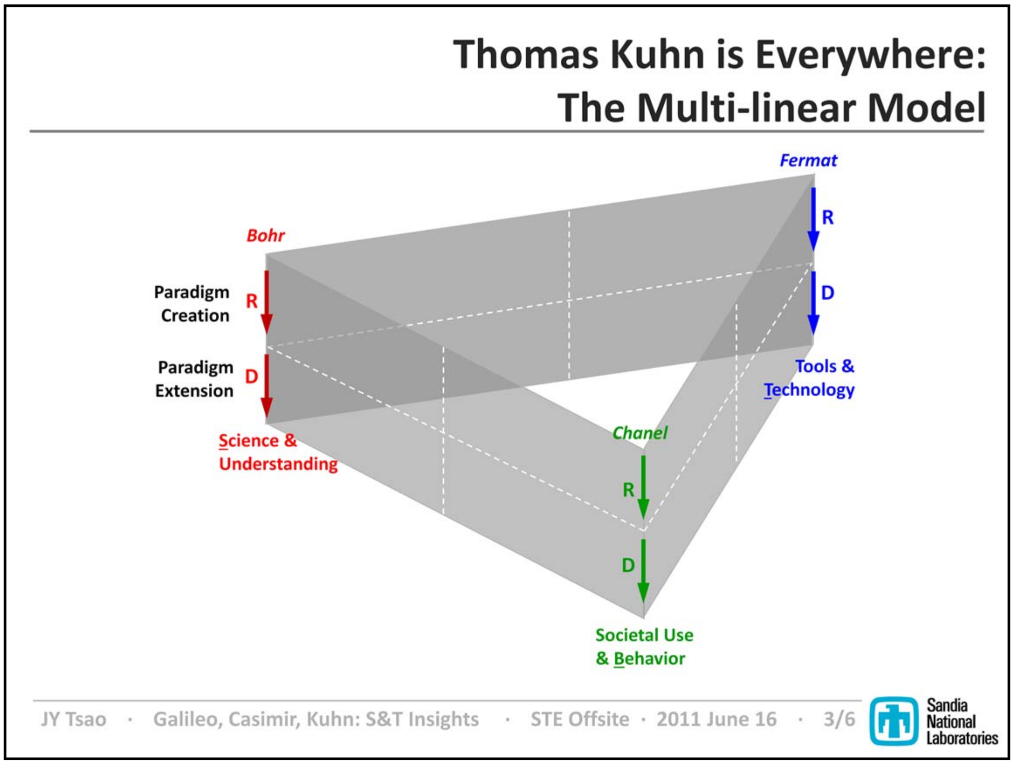
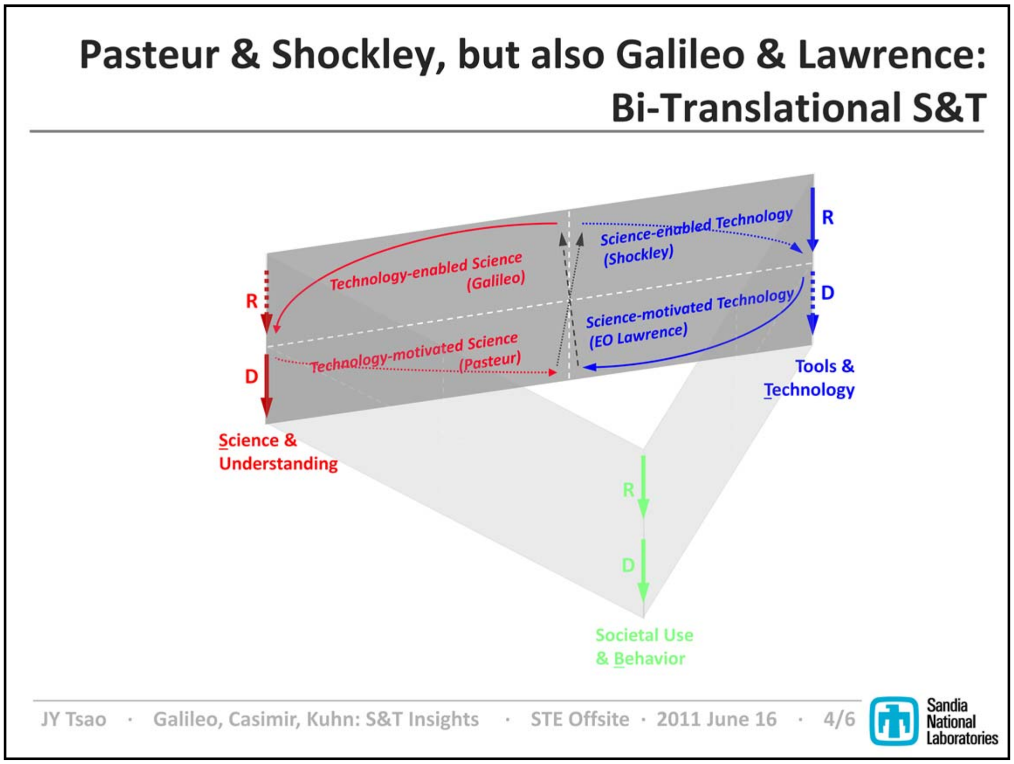
- Thanks, Marie. And thanks, Jerry and Steve, for inviting me to provide this short bit of comic relief to your day today.
- Let me start by saying you guys have a really tough job. You're re-engineering a very complex social system: the S&T enterprise at Sandia. And it's especially tough for at least two reasons.
- One reason is obvious: you're re-engineering a system within which you yourselves are actors, so it's hard to maintain a sense of objectivity and impartialness.
- Another reason is perhaps not so obvious: when you engineer a complex physical system, you usually have some tools and technologies, or some scientific understanding, to guide you. When you engineer a complex social system, there aren't many tools and technologies, and there isn't much scientific understanding, to guide you. So you have to do it from hard-earned experience, and from the insights you have gathered from that experience.
- In fact, there probably isn't a group at Sandia with more hard-earned experience in this area than you all, so, to be honest, I'm not sure what I can really add. But if there is anything I can add that will help make your job easier, I'd like to. And one thing that maybe I can add, or that Jerry thought I might be able to add, is to gather for you some small insights from the emerging field that some people call the "science of science," and perhaps some of those insights will resonate with you and be of some use.
- I put these pictures of Thomas Kuhn, Galileo Galilei, and Hendrik Casimir up, because these insights can be traced back to their careers as philosophers, practitioners, and managers of science.



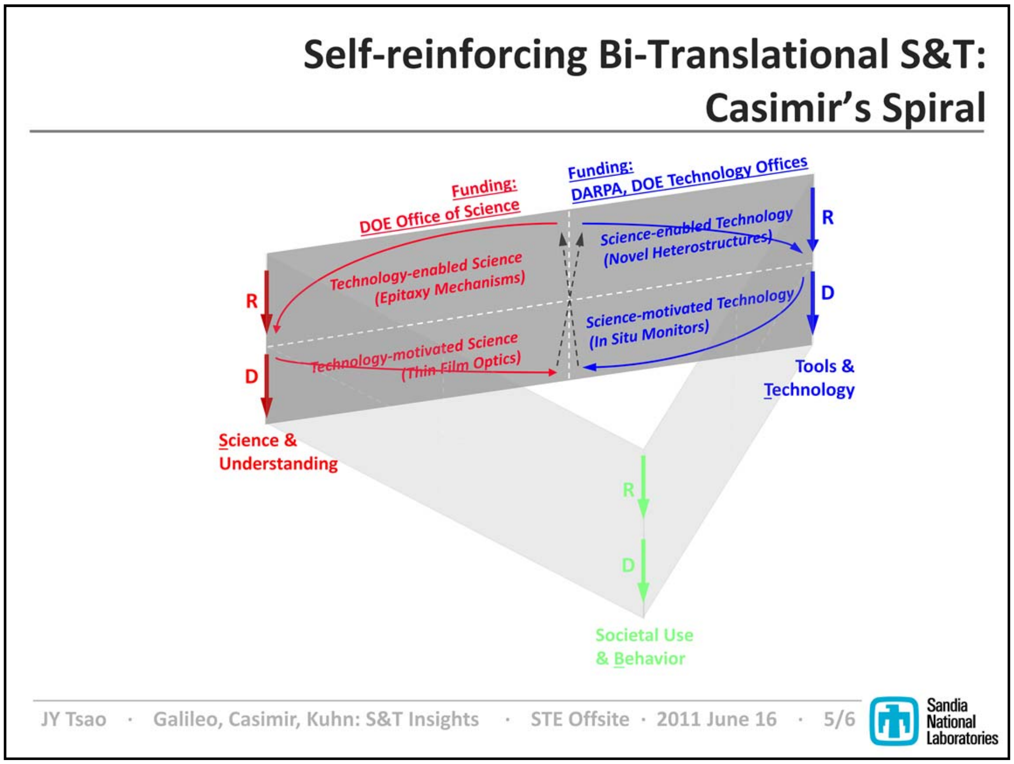
- Let me start with the most common way of viewing an S&T enterprise: the so-called linear, or pipeline, model sometimes associated with Francis Bacon, the 17th century English philosopher, definitely associated with Vannevar Bush, the architect of post-World-War-II science policy in the U.S.; and often used by our own Department of Energy.
- I probably don't need to say much about this model, because it's so simple. The scientist is the hero: starting from grand challenge research to discovery research, to use-inspired basic research, his or her work spawns the applied research and technology maturation and deployment that the rest of society benefits from. This chart at the top you've all seen from the DOE Office of Science; this chart at the bottom is from the DOE Office of Energy Efficiency and Renewable Energy. There are some bi-directional flows down here, but by and large what you see from both of these charts is a linear flow from left to right.
- What's curious about this model is that, despite its popularity, there probably isn't one person who has thought seriously about the science of science who believes it makes much sense.



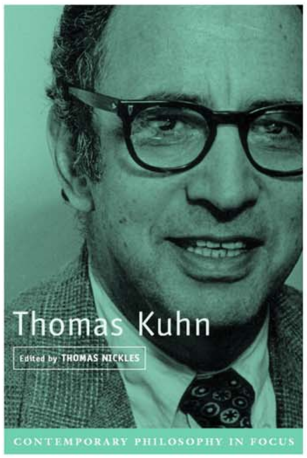
- Of course, it's easy to say what doesn't make sense; it's a lot harder to say what *does* make sense, and by no means has the science of science coalesced around what does make sense. But there are small insights that I thought might be useful to you if I brought them together in a certain way. To depict these small insights, I've drawn a three-dimensional triangular diagram. Don't take the diagram itself too seriously; it's just a means to convey the insights.
- The first small insight is that scientists aren't the center of the universe; knowledge doesn't all flow from them. They are one very important leg of the triangle, but they are only one leg. Technology is another important leg; and societal behavior is yet another important leg. And, though these legs have much in common, and obviously interact with each other, they are also distinct. As exemplified by Neils Bohr, one can pursue scientific understanding without the thought that this might lead to new technologies or to new human behavior. As exemplified by Pierre de Fermat, one can pursue tools, like mathematics, without the thought that these might be useful to science or to human behavior. And as exemplified by Coco Chanel, one can introduce new forms of human behavior, like clothing fashions, without necessarily drawing upon science or technology.
- The second small insight is that Thomas Kuhn is everywhere; paradigms are created and extended, and old paradigms die, in each of these legs, all the time. And if we loosely identify research with paradigm creation and development with paradigm extension, R&D is also everywhere.
- In other words, research and development isn't linear, it's multi-linear, occurring in these three legs simultaneously and not necessarily interactively. In some ways, you are doing exactly that right now. You are trying to introduce new organizational behaviors based on your experience with previous organizational behaviors, but you are not necessarily drawing upon a scientific understanding of organizational behavior, nor on tools that would make your jobs easier.
- Of course, to say that the three legs don't necessarily interact, doesn't mean that they don't interact. One could argue that it is precisely their interaction that makes the triangle so powerful and productive.



- How might one think of those interactions? Well, since science and technology are at the heart of what you all are discussing today and tomorrow, let's zero in on interactions between those two legs. So here I've grayed out the societal use and behavior leg, and drawn arcs connecting science to technology as well as technology to science. Don't take the positioning of these arcs too seriously, they are just intended to catalog their existence and to convey a sense of directionality.
- Two of the arcs are the ones that are present in the linear model, the model in which science leads to technology. There's science-enabled technology, exemplified by William Schockley and the invention of the semiconductor transistor. Then there's technology-motivated science, exemplified by Louis Pasteur and the development of the science underlying germs and disease. This is of course the use-inspired science that Donald Stokes introduced in his book "Pasteur's Quadrant." And if you trace all of the dotted lines or arcs, you basically get the scientist-centric DOE Office of Science view of the universe that starts from grand challenge and discovery science and winds its way to use-inspired science and eventually to technology development. This is also what the National Institutes of Health would call translational science: medical science that makes an impact on medical technology.
- But this of course is only half of the story, and for some not even the most important half. The other half of the story are the two arcs that go in the reverse direction, from technology to science. There's technology-enabled science, exemplified by Galileo and his use of the just-invented telescope to observe the moons of Jupiter. Then there is science-motivated technology, exemplified by Ernest Lawrence and his development of the cyclotron for studying the structure of atoms and nuclei. And if you trace all of the solid lines or arcs, you get the technologist-centric view of the universe that starts from technology breakthrough and winds its way to science-motivated technology and finally to science itself.
- Some argue that translational science, where science leads to technology, is more important. Others argue that translational technology, where technology leads to science, is more important. I don't know that it's all that important to argue either way. To my mind, *both* are important, and that bi-translational S&T is a better way of describing what actually goes on in a real S&T enterprise.



- So what might these little insights mean for Sandia? Well, to my mind, Sandia is positioned very nicely to contribute to bi-translational S&T, because within one institution it combines strong efforts in both science and technology. In fact, I am sure many of you have observed over the years, as I have, magical moments when bi-translational S&T forms a self-reinforcing positive feedback loop in which scientists and technologists feed, and feed on, each other to make breakthroughs in science and technology both. I call this kind of virtuous spiral Casimir's Spiral, because Hendrik Casimir, the Dutch physicist and for many years the Director of the famous Philips Laboratory in Eindhoven, was the first, as far as I can tell, to talk about it in a serious way.
- Maybe some of these magical moments will be part of the stories that we'll hear about after lunch. I know in my own career in compound semiconductor materials and devices, one magical moment came when the science of epitaxy and devices came together with the technology of epitaxy and devices, and all sorts of breakthroughs were made, including the 50%-efficient vertical-cavity surface-emitting laser. And, perhaps not surprisingly, our sponsors for the science part, mostly the DOE Office of Science, and our sponsors for the technology part, mostly DARPA but also DOE, were both happy as could be.
- Now, why these magical moments sometimes happen and more often don't, I have no idea. But when they do I believe they are very big deals. They are inspiring to everyone who is involved in them. And of course they represent outsized bursts of creativity and contribution to both science and technology.



- With that, I guess I'll end, and pay my respects to three giants in the science of science: Kuhn, Galileo and Casimir.