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A New Framework for Science and Technology Policy

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The usual divisions of science and technology into pure research, applied research, development, demonstration, and production creates impediments for moving knowledge into socially useful products and services. This failing has been previously discussed without concrete suggestions of how to improve the situation. In the proposed framework, the divisive and artificial distinctions of "basic" and "applied" are softened, and the complementary and somewhat overlapping roles of universities, corporations, and federal labs are clarified to enable robust partnerships. As a collegial group of scientists and technologists from industry, university, and government agencies and their national laboratories, we have worked together to clarify this framework. We offer the results in hopes of improving the results from investments in science and technology and thereby helping strengthen the social contract between the public and private investors and the scientists-technologists.

We suggest a new framework in which four interdependent facets of the science and technology enterprise arise naturally from work on how human beings approach system level complexity. The model by Elliott Jaques is most applicable and defines four fundamentally different and complementary approaches: direct action, cumulative, synthesizing (also known as system-level serial), and synergizing (also known as system-level parallel). In a sense, our taxonomy is based on the collective development of humans as they have tackled difficult challenges and created major innovations like the tribe, agriculture, money, and the scientific process. We have also observed the same four processes as the four types of strategy in executive-level simulations of public-private cooperation.

A framework should clarify the necessary, sufficient, and complementary aspects for a complete solution, e.g., the framework of the legislative, executive, and judicial branches of government. Each facet depends on the others. When applied to science and technology, the right framework should reveal a concise, coherent, and comprehensive proto-policy to guide us through the next century. The four parts of this framework are Pioneering, Integrative, Mission Directed, and Synergistic and are best represented by the four facets of a tetrahedron illustrated in Figure 1, with each having a boundary in common with the others.

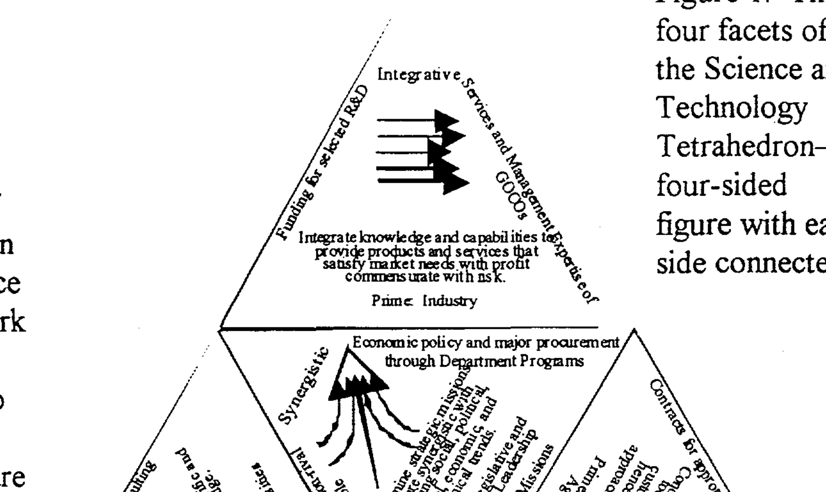


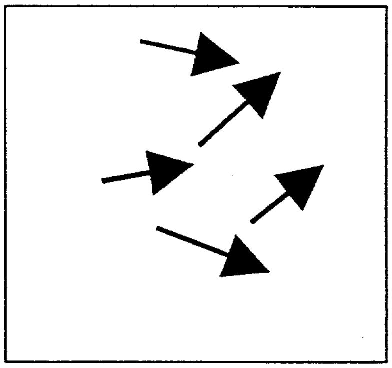
Figure 1. The four facets of the Science and Technology Tetrahedron—a four-sided figure with each side connected.

DISCLAIMER

In the following four sections, each aspect is described, graphically illustrated with an icon, examples are given, and each aspect is differentiated in terms of risk management, accountability, cultural imperatives, relationship with sponsor, competitive considerations, and interfaces for partnerships at the boundaries with the other facets. Then the framework is applied to a problem of the day.

Pioneering

Pioneering describes the multitude of researchers and innovators who push the frontiers of knowledge using their own discretion, judgment, and passion to create new order and understanding out of apparent randomness. Collectively they provide the excitement of discovery that energizes the enterprise with both basic and applied research and with technical innovation to fend off stagnation. Through this facet, experiments test nature in much the same way as entrepreneurial-business ventures test the market; both are grounded in an external and unforgiving reality. Professional societies, journals, and the peer review process play an invaluable role of facilitating the Pioneering facet to achieve a working consensus of where to go next and what should be advanced, at the expense of other options.



The self-correcting mechanism of the scientific process separates authentic results from flawed results and tests them against the social norms. Kuhn's Structure of Scientific Revolutions provides insights into this enriching type of science. Because of the diversity of approaches, the appropriate icon for visualizing this type is a collection of arrows that point generally forward but with a lot of variation. The university is the principal—but not the only--home of Pioneering science and technology.

Examples from universities:
Examples from industry:
Examples from government laboratories:

Differentiators for the Pioneering Aspect

Risk Management: Portfolio diversification, peer review, the expectation of surprises during the discovery process, and replication of important results manage the risks in this category. The large number of projects from a large and diverse set of subjects provides risk management by portfolio diversification. The peer review process, the associated track record of principal investigators, and the judgment of the accountable program managers in the sponsoring agencies provide adequate risk management for individual projects. Since the principal expectation is to learn something new and the consequences of failure are mostly lost increments of opportunity (not the well being of society), surprises are generally accepted as part of the Pioneering process and the risk of failed expectations is accepted as part of the discovery process. Finally, independent teams replicate important results and catch mistakes or deceit before the consequences become too large.

Accountability: Two processes provide adequate and informed accountability:
The principal investigator is personally accountable to his or her sponsor for completion of the promised work. In addition, professional accountability requires the principal investigator to present his or her findings for critique and replication by peers.

Cultural Imperative: Personal freedom and independence drive behaviors within a tenure system that is initially competitive and then becomes collegial. The result is a prestige-based professional system.

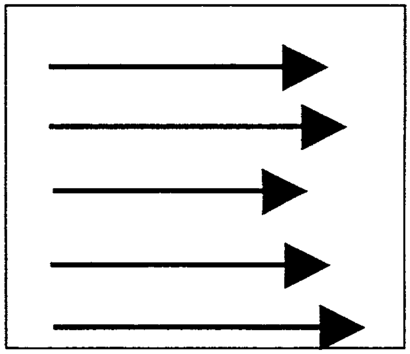
Relationship with Sponsor: Relationships are often based on long-term support of a continuing series of programs and become collegial over the years.

Competitive Considerations: Grant writing process is very competitive—particularly with new researchers still establishing themselves. Getting tenure (or its *de facto* equivalent) is very competitive.

Interfaces for Partnerships: Funding flows from the Synergistic, Mission-Directed, and Integrative aspects. The Pioneering aspect provides consulting to the Integrative and Mission-Directed communities. Information for the purposes of persuasion flows from Pioneering to the Synergistic aspect.

Integrative

In the integrative mode, people combine many results to generate new innovations with pragmatic outcomes. A strongly unifying goal necessarily guides the complex process forming a complete solution from multiple concepts. Because of the characteristic accumulation and alignment of the contributing success factors, the appropriate icon for visualizing the cumulative mode is a collection of arrows pointing in the forward direction. For example, the quest to satisfy a market need and provide a good return on investment guides the process in industry and encourages relatively short-term investments. Although public-sector teams also practice this process when the payback time is too long for private investors, industrial teams of researchers, developers, marketers, and managers are the principal practitioners of the cumulative mode.



Examples from industry:
Examples from government laboratories:
Examples from universities:

Differentiators for the Integrative Aspect

Risk Management: From the point of view of the provider of funding, the defined risk must be justified by the expected benefit, e.g., sufficient profit to justify the investment of assets in this project rather than in alternative uses. To make such an assessment, the proposal must have well-defined tasks that can be formulated into a statement of work with defined benefits and risks and competed with other uses of the available funds. In industry, senior management reviews the proposal against internal-rate-of-return standards and manages risk by approving or disapproving the work. The usual standards for internal rate of return and the avoidance of risk combine to favor relatively short-term projects with a high probability of meeting expectations.

Accountability: Line accountability in organizational hierarchy leads from shareholders to board to management.

Cultural Imperative: Increasing the profits for the company and increasing the market value motivate the decision makers in for-profit companies. Providing excellent stewardship of the entrusted funds provide a related motivation in not-for-profit entities.

Relationship with Sponsor/Customer: The relationship with a sponsor or customer is often arms-length or implicitly adversarial within the shared goal of completing the work successfully. In the competition for funds, the relationship is inherently adversarial in that the science-and-technology provider maximizes the sales price within the constraints of competition and minimizes the project costs to increase margins and profits or discretionary funds); the customer minimizes sales price by competition.

Competitive Considerations: Prices are regulated by competition.

Interfaces for Partnerships: Major funding is generated from market driven success with customers, some of whom are in the Mission-Directed aspect. Information and persuasion flow to the Synergistic aspect. Consulting comes from (and funding goes to) the Pioneering aspect.

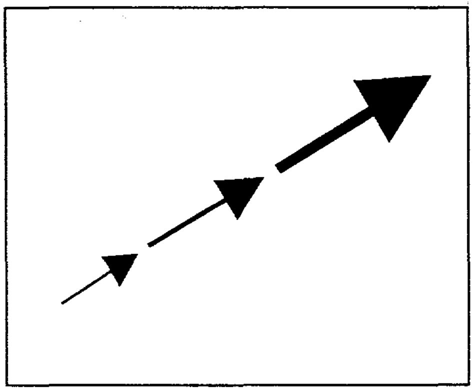
Pioneering and Integrative aspects are insufficient to meet some national challenges. Some projects are too complex for the Pioneering aspect and too ambiguous for the Integrative aspect to formulate and evaluate the corresponding risks. These include the following examples:

- Managing the increasing complexity of interdependent systems
- Reducing healthcare costs while improving the quality of life
- Clean and sustainable environment
- Safe, secure, and reliable energy

- Countering the potential for the proliferation of weapons of mass destruction
- Countering crime
- Solutions for aging infrastructure
- Countering Cyber and Physical Terrorism

Mission Directed

This facet addresses some of the major problems and opportunities of a society, as a whole, that lie outside the constraints of a private investment-deployment-profit system. Motivated by urgent social benefits, Mission-Directed projects are sustained sufficiently long for real solutions with great depth complexity (a lot of benefit inherent in a small beginning) to emerge and mature. The maturation process creates its own energy in a self-organizing way as a growing market creates its own Mission-Directed coherence.



Characteristically, partnerships among industry, academia, and government in the Mission-Directed aspect make each achievement the springboard for increasingly more powerful achievements. The corresponding visual icon features a series of arrows of increasing weight and power connoting the succession of evolving achievements.

For example, when the technology of electromechanical switches could no longer meet the telecommunication needs of society, a need for a fundamentally new solution was identified. A research group at Bell Laboratories—which was the equivalent of a national laboratory for a regulated monopoly at the time-- was tasked to find a smaller, cheaper, lower-power-consuming, and more reliable switch. Quantum mechanics from the Pioneering aspect permitted the synthesis (a characteristic of the Mission-Directed aspect) of materials science and electronics to understand and create transistors. The Mission-Directed aspect sustained the work and stimulated technical innovation in the Pioneering and Integrative aspects until the detrimental influence of the sodium impurity was finally identified and eliminated by a for-profit company to make a useful device. The self-energizing nature of the Mission-Directed aspect drove innovation in both the private and public sectors through the integrated circuit stage, the microprocessor stage, and into the information age.

Examples from government laboratories:
Examples from industry:
Examples from universities:

Identifying the urgent needs of society and formulating and sustaining a Mission-Directed aspect is a political leadership issue for the nation in a highly participative process, as it was for the corporate leadership of the phone system in the 40's and 50's. The mission agencies, through their laboratories, are the principal additions to the research universities and industry to produce the Mission-Directed aspect.

Differentiators for the Mission-Directed Aspect

Risk Management: In Mission-Directed work, the consequences of failure are usually too great for the low-consequence-of-failure nature of the Pioneering aspect. In addition, the probability of failing to achieve a direct return on the investment is significant and the consequences of failure are difficult to quantify and, hence, to limit in a fixed-priced contract. In some cases, a cost-plus-fixed-fee contract can solve the problem, but the conflicting interest of the customer-supplier model deter use of this vehicle in very ambiguous issues, like those listed above. Therefore, Mission-Directed work is not well suited to the risk/reward standards of today's for-profit corporations in the Integrative aspect of science and technology. Therefore, the sponsor entrusted with addressing the issue manages the risk with the regulated-monopoly model of organizational relationship--keeping the supplier of science and technology close enough to trust by closely auditing how the work is being accomplished. The agencies of the executive branch are entrusted with Mission-Directed Work. Those with national or federal laboratories closely audit the practices and performance of their laboratories in a manner that would be unacceptably intrusive in private industry.

Accountability: Government accepts accountability to the public for the risk associated with the complexity of ambiguously defined taskings at the mission level. Government owns and controls access to capability as a regulated monopoly.

Cultural Imperative: Service in the national interest motivates participants above prestige, freedom, and cash compensation.

Relationship with Sponsor: Collaborative partnering dynamically manages the risk by updating the action plan based on interim results. Long-term commitment suitable for must-succeed missions sees the system through the periodic setbacks of high-risk work.

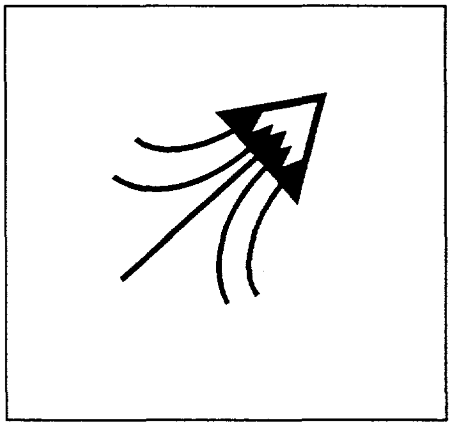
Competitive Considerations: Public opinion about salaries of government employees make it difficult to attract sufficiently qualified personnel in sufficient numbers to work in this facet with modest prestige, low freedom, and mediocre cash compensation. The Government-Owned and Contractor-Operated (GOCO) arrangement ameliorates some of these difficulties.

Interfaces for Partnerships: Funding primarily comes from the Synergistic facet with derivative funding from the Mission-Directed and Integrative facets of science and technology. The Mission-Directed activity provides user facilities for the Pioneering facet, often through "partnerships." Information flows to the Synergistic facet to assure informed planning.

Synergistic Science

In contrast to the serial process of technology-driven growth in the Mission-Directed mode, the Synergistic mode is a parallel process for leveraging the social, political, economic, and technological trends in global society. The process identifies the missing technological advancements that--when they mature--will combine synergistically with those that would be there anyway--to enable unprecedented opportunities for the well being of society. The power of the idea sustains the process.

The visual icon for synergistic science is a coherent array of arrows that combine with each other to form a macro arrow of greater significance. The Synergistic mode provides the missions for the Mission-Directed aspects of science and technology and provides the context for the rest.



In the post WWII era, the relevant trends included the renewed openness within the community of democracies, the consensus for rebuilding market economies, the economic demand for consumer products like television, and the technological opportunities of newly developed computers and more access to space. These trends combined synergistically with the trend of solid-state consumer electronics (sustaining the development of smaller, cheaper, lighter technologies and electronic products) to enable the global information age. In this case, the synergistic mode emerged from the collective behavior of many stakeholders. This emergent form will continue.

In addition, President John Kennedy practiced the synergistic mode when he declared a national goal of going to the moon as the technological initiative arising from the political, social, and economic trends of the early 1960s. As the elected leaders of the most technologically advanced nation, the executive and legislative branches of the US Government can exert leadership through the Synergistic mode for far-reaching technology initiatives that fulfill social, political, and economic needs within current moral and cultural trends.

Differentiators for the Synergistic Aspect

Risk Management: Legislative authorization is separated from Executive advocacy and implementation to manage risks through a balance of power.

Accountability: The voting public elects officials who are accountable at each election for their performance on the major issues of the time and between elections under the balance–of-power provisions of the government.

Cultural Imperatives: Rendering public service and exercising the power for doing good in historic work motivates the practitioners of the Synergistic facet.

Relationship with Sponsor: Networking and persuasion leads to election and re-election

Competitive Considerations: The political process provides checks and balances by competition between parties within an election and competition and negotiated collaboration between the majority and minority divisions of the Legislative Branch and between the three branches of government.

Interfaces for Partnerships: Funding from the tax-paying public flows to Mission Directed (and through them to Pioneering and Integrative). Information and persuasion flows from all of the other facets to the Synergistic facet.

Application of the New Framework

We will apply the framework to one or two national issues that will be suggested by the editors of ***Issues in Science and Technology*** *to show how the integrated model can solve higher–level problems more expeditiously than the current linear model. We have listed some candidate issues in the following table but solicit guidance on what issue or issues might be most important to develop with this framework and suggest how the outcome will be different with the new framework than it would be today.*

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List of Candidate Challenges to Illustrate the Need for the Full Taxonomy for Science Policy

Issue	Possible Sources for Scientific and Technical Contribution
Reducing the costs of health care without reducing the quality of care	Bioscience through genome research and application, physical chemistry through more efficient pharmaceutical research, and computer science through information management
Managing the social costs of the aging population	Bioscience through genome research and application, physical chemistry through more efficient pharmaceutical research, and computer science through information management
Reducing the cost of regulation	Sufficient knowledge base for effective action based on risk and consequence and a more technically literate public to accept the solution confidently
Increasing productivity in the service sector--in which about 70% of Americans are employed to produce approximately 25% of the GNP with only a 0.8% improvement in productivity per year.	Computer science and related information technologies
Improving energy global supply and environmental quality simultaneously and affordably	New environmentally conscious energy sources, "disruptive" technologies like the Next Generation Vehicle, and computational science for understanding implications of human activity on the environment and supporting political action to mitigate impact
Increasing the quality, accessibility, and affordability of education	Cognitive psychology, computer science and electrical engineering enabling the information revolution
Mitigating the social effects of the concentration of wealth at the high end to assure that there is no credibly insurmountable barrier to individual attainment that could destabilize US society	Information sciences and technologies that increase the value of an hour's work and increase effectiveness of education and training

Assuring the safety, reliability, and security of the US infrastructure	Information sciences and technologies
Reducing the international tensions that dominate our foreign policy and corresponding defense policy	New environmentally conscious energy sources

Suggestions for Further Reading

Readings on the deficiencies in the Linear Model of Science and Technology: **International Encyclopedia of Unified Science, V 01, Structure of Scientific Revolutions,** Number 02, by Thomas S. Kuhn, University of Chicago Pr. 1962

Pasteur's Quadrant: Basic Science and Technological Innovation, by Donald E. Stokes, Brookings Institution Press, 1997

Readings on the basic human processes for addressing complex issues: **Human Capability,** by Elliott Jaques and Kathryn Cason, Cason Hall & Co., Publishers Ltd., 1994