A FRAMEWORK FOR UNDERSTANDING TECHNOLOGY AND TECHNOLOGICAL CHANGE

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Abstract

Technology is described as a space matrix with three dimensions. Technological change is defined as a change in the dimensions of the space matrix, with technological progress defined as a net increase in the overall dimensions of the space matrix. The space matrix conceptual framework is compared and contrasted with several schools of economic thought on technology and technological change. Factors governing changes in each of the dimensions of space matrix are analyzed, often using very basic economic concepts. A number of general conclusions follow from the perspectives gained in the course of describing the conceptual framework.

Keywords: Framework, principle, technological change, matrix, space

Introduction

Presently there is a tremendous volume and diversity of literature being published on technological change. It is feasible for very few individuals to be intimately familiar with the entire range of study and the details of each. Such numbers and diversity of information makes focusing on essentials and priorities difficult. A recent historical survey on the diffusion of innovations from a microeconomic perspective argues that the three-part linear model of innovation (i.e., invention, innovation, and diffusion) while perhaps oversimplified, still serves as a useful "organizing principle" in understanding technology and technological change (Hall 2004). This paper attempts to describe a different, more detailed, but still useful "organizing principle" for understanding technology and technological change.

The framework described here does not depend on a sophisticated mathematical analysis of technological changes, yet has a strong quantitative rather than qualitative orientation. The framework has much more in common with economic and modeling methodology than behavioral, case study, or statistical approaches. Accordingly this paper will reference only applicable economic and modeling literature, even when the subject matter is also dealt with by other disciplines and approaches.

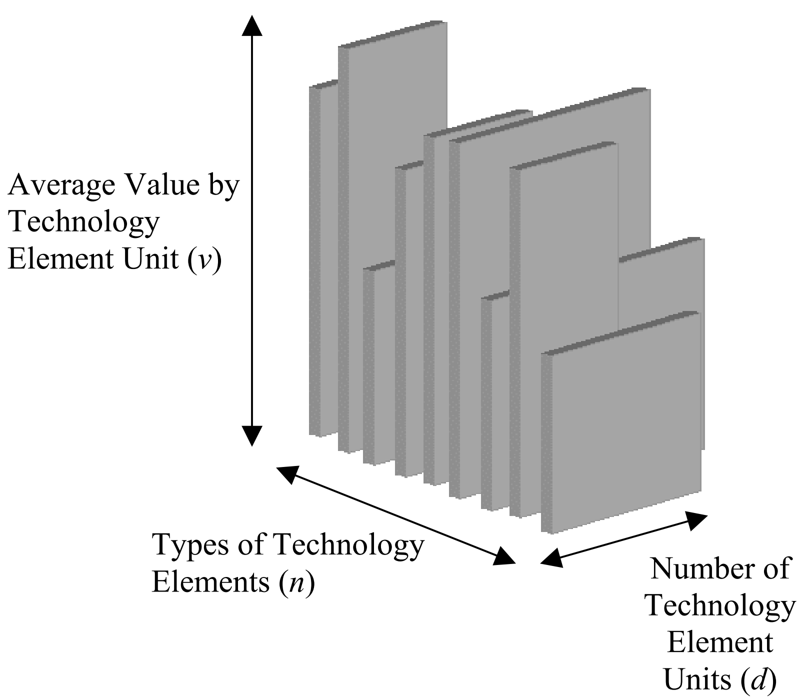
Derivation of the technology space matrix

We begin the derivation of the general conceptual framework by stipulating that an invention or innovation is a new good, service, or process that might be used to satisfy societal needs. A specific type of good, service or process will be hereafter referred to as a *technology element*. Technology elements comprise the first of three basic facets of the technology and technological change framework proposed in this paper.

Obviously, the accumulation of different kinds of inventions and innovations (i.e., the accumulation of technology elements) is an important aspect of technology and technological change. A society, however, that accumulated only one or a small number of each kind of invention or innovation would probably be considered technologically backward. The Soviet Union in the 1950's produced such a small number of technology element units, particularly consumer goods that the vast majority of the Soviet population lived as though such technology did not exist. Even though in a few areas such a restricted technology base could temporarily outpace a more broad-based technology, as it did outpace the West for a time in rockets and space, such a lead was quickly overcome. In an analogous way that the numbers of units associated with each technology element matter in technology, the amount of use made of each technology element also plays a role. If cell phones are numerous, but no use is made of them, they might as well not exist as far as technological level of the society is concerned. The *diffusion* of technology elements (defined here as the number of technology element units or amount of use by technology element unit) constitutes a second facet of the technology and technology change framework.

Any discussion of the meaning of technology and technological change must take account of the fact that some technology elements are more valuable than others. More valuable does not necessarily mean the purchase price of one technology element unit is higher than another. The meaning intended is that the more valuable technology can displace or substitute for units of the less valuable technology (e.g. as horseless carriages substituted for and then displaced the horse and buggy). In some cases of radically new technology elements it is not immediately obvious what is being substituted for or displaced, but with thought or research one can always make such a connection, even if the connection is indirect. What, for instance, did the discovery and provision of electric power substitute for or displace compared to the technology of the early 1800's? The answer is nearly everything—candles for lighting, wood and coal heating, skilled labor, tooling of all kinds, etc. It is interesting to note that this substitution and displacement of older technologies by electric power occurred in combination with other technology elements, not just through the introduction of electricity alone. Some technology elements like telephones need numbers of other units of a similar type to have value. Some, perhaps most, technology element units need other technology elements (as well as numbers of units) to be effective and valuable (e.g. an automobile needs numerous gasoline stations and paved roads). Value by technology unit is the third facet of technology change framework.

Based on the preceding terms and discussion, technology at a given point in time can be represented by the number of technology elements present, the extent of the diffusion of those technology elements in the economy and society, and the value contributed by each technology element unit, either individually or in conjunction with other elements. The verbal description suggests the following graphical representation of a three-dimensional *technology space matrix*:



The technology space matrix is what is meant in this paper by the term *technology*. The size of the technology space matrix can be taken as a descriptive gauge of the usefulness or power of a technology set. *Technology change* can be defined as a change in the dimensions of the technology space matrix. *Technological progress* can be defined as a net increase in the matrix. In this framework, the problem of understanding technological change is reduced to one of understanding how ***n***, ***d***, and ***v*** change (or are made to change) over time.

An example of the technology space matrix concept is provided by the introduction and growth of television technology in the 1940's through the 1970's. In the 1940's practical televisions were introduced to a wide commercial market. Television technology constituted an increase of one in the number of technology elements (*n*) in the technology space matrix. During the period 1940 though 1970, the numbers of television sets in use expanded greatly, as did the average hours of use per household. This constitutes an increase in diffusion (*d*) over the period. Along with the expansion in numbers of television sets and their use, the perceived value (*v*) of television to individuals and society expanded, as indicated by the amount of money spent on television purchases and the willingness to give up time and other pursuits to make way for this technology.

The technology matrix concept is defined above at the technology element unit level of technology element aggregation. The reason for basing the technology space matrix on real individual units of goods and services is that the utility and power of a technology does not result from abstractions:

> The productivity and welfare enhancing powers of a new product are only realized when the product is adopted by its potential users (Götz 1997).

The technology space matrix concept can, however, accommodate analytically convenient aggregate classifications of technology element types, (e.g. aerospace, pharmaceuticals) along with the associated numbers of technology element units, and combined or average unit values.

As far as this author has been able to determine, the technology space matrix technology conceptual framework is unusual in that it concurrently:

1. Identifies technological change solely with changes in the number of technology elements, extent of diffusion, and unit values
2. Measures the power and utility of a technology set by means of quantities associated with these variables
3. Equates technology with artifacts and processes rather than knowledge or abstract entities
4. Includes all useful goods and services as components of technology with the potential to be involved in technology change

While the technology space matrix concept apparently differs from most other technology conceptual frameworks in the ways listed above, it also has much in common with mainstream technology theories and concepts.

Thinking of technology as a *space* is not unique to this paper or technology space matrix. Almost any attempt to approach the subject of technology from a quantitative perspective leads naturally to the concept of a space with associated dimensions. Even if a space is not explicitly referred to, mathematical models, formulas and constructs dealing with technology frequently *imply* such a space. As a result, explicitly or implicitly, many mathematically oriented papers on technology development theory share this similarity with the technology space matrix.

In one form or other, the three basic variables comprising the technology space matrix dimensions are frequent objects of study in economic technology literature, although usually at aggregate rather than unit levels. Circumstances governing change in the number of technology elements, i.e., inventions and innovations, and the diffusion of technology have been important objects of study by historically oriented or "evolutionary" economists starting with Joseph Schumpeter. The current version of the evolutionary theory has been referred to as evolutionary theory of economic change or ETEC (Dosi and Winter 2000). In the ETEC literature technology element value has generally been encompassed within the description of inventions/innovations or of diffusion. The more mainstream "neoclassical" and "new growth" schools of economists generally shy away from research on the basic mechanisms governing change in the number of inventions and innovations and the diffusion process, although a limited amount of diffusion-related study focuses on the effects of differing "vintages" of capital investment. The new growth school can, however, be said to be very interested in the aggregate value of technology elements in the form of their interest in the ways that the productivity of capital and labor may change, part of which can result from negative or positive complementarities between technology developments.

The technology space matrix, being composed of the aggregate of all inventions and innovations that have been accumulated over time, implies not only that more technology can translate to economic growth, but also that a larger economy can be a factor in technology growth. Such a result appears to be in line with the thinking of new growth economic theorists. *Growth Theory* (Solow 2000) states:

> At a very general level, that paper [Arrow's] works on the assumption that the level of technology depends on the amount of capital that has already been accumulated…
>
> In this model technological progress [Romer's] consists of finding new *varieties* of capital goods, that is, not so much in making some kinds of capital goods more productive as making more kinds of capital goods.
>
> In this model [Grossman and Helpman]…the major source of a fast rate of innovation …is *scale*…a large economy will grow faster than a small economy.

Details on the three fundamental technology space matrix dimensions and associated change factors

This section provides conceptual detail on the idea of technology elements, the diffusion of technology elements, and element unit value as they are employed in the technology space matrix framework. It is intended to illustrate the operation of the conceptual framework and at the same time provide additional perspectives on ***n***, ***d***, and ***v*** in addition to those found in other works.

Factors governing changes in the number of technology elements (*n*)

Evolutionary economists and modelers discuss a variety of factors or conditions that impact the number of inventions and innovations. These include, e.g., (Fagerberg 2000):

Entrepreneurial drive
New innovations tend to facilitate or enhance others
Market-driven environmental selection processes
The persistence of technical paradigms and paradigm shifts
Feedback loops between developers and between innovations
Social, institutional, and political factors
Firm behavior and routines
Increasing returns to scale
R&D funding and size of firms
Degree of variation in technologies and knowledge
Vintage and rate of capital investment
Chance

The technology space matrix discussion in this section focuses on a smaller set of factors that appear to have academic support in economic and modeling literature as having a role in new technology developments:

(1) Quantity and quality of scientific and technical personnel and other resources available for development
(2) Risk and rewards associated with development
(3) Competition between developers
(4) The current state of technology

Although the technology space matrix discussion factors were not derived from the ETEC list they can be seen as generally corresponding:

Quantity and quality of scientific and technical personnel and other resources available for development:

-- R&D funding and size of firms

Risk and rewards associated with development

--Social, institutional, and political factors
-- Increasing returns to scale

Competition between developers

-- Entrepreneurial drive
-- Market-driven environmental selection processes
-- Firm behavior and routines
-- Vintage and rate of capital investment

The current state of technology

--New innovations tend to facilitate or enhance others
--The persistence of technical paradigms and paradigm shifts
--Feedback loops between developers and between innovations
--Degree of variation in technologies and knowledge
--Chance

Quantity and quality of scientific and technical personnel and other resources available for technology development

Based on historical experience it is a reasonable assumption that the more and better scientists and engineers there are in a field of technology, the more likely it is that technological advances will occur, and/or that the speed of innovation will be faster, barring the exception that there can be too many people on a project for efficient communications. The proposition that there is a direct correlation between expected technical progress and the number of qualified personnel presupposes, of course, that a corresponding quantity and quality of tools and other material requirements needed to support their work is also available. *R&D, Innovation, and Technological Progress: A Test of the Schumpeterian Framework without Scale Effects* (Zachariadis 2002) is an example of research findings that support the assumption of a positive link between the quantity of properly supported technologists and technological progress. In subsequent discussion, ***r*** will represent the combination of quantity and quality of resources available for technology development.

Risks and rewards associated with development

Except for the type of risks and potential rewards, investment in future technology appears to be similar in principle to investing to achieve a greater output of conventional goods and services:

> …R&D investment decisions are governed by the cost of R&D and its expected return (Jaffe, Newell and Stavins 2000).

Both conventional and technology investments require near-term sacrifices to achieve long-term gains, and both generally entail someone or some entity to take risks. An obvious difference, however, between investing in conventional versus new technology is that the new technology generally involves more uncertainty and risk, while accompanied by the potential for a greater than normal return (Jaffe, Newell and Stavins 2000).

From an investor's point of view, greater risk lowers the expected value of the payoff on the investment. Therefore, to be viable candidates for investment, risky (e.g., technology) projects need to have greater potential payoffs—before taking account of probability--than less risky (e.g., conventional) ones. Technology projects and other risky projects look more viable when the prevailing interest rate is lower. This is due to the likelihood that the technology project will have a larger net return after repaying invested funds plus interest.

We have been discussing rewards as if they were the only motivation for innovation and the attendant sacrifices that are a necessary preliminary to innovative accomplishments. Rewards, however, can also be negative. Sanctions—the spur of actual or feared adverse consequences if an innovation is not pursued—have historically been important sources of motivation for technical achievements. Sanctions have been an important factor not only in the accomplishments of totalitarian regimes like Nazi Germany and Soviet Russia, but also in Western countries. The successful U.S. development of the atomic bomb was arguably more due to the concern about the consequences of the "other side" being first with a bomb than any rewards and incentives provided to its developers.

More often sanctions limit technological development. In the U.S. and other litigious countries, for example, the threat of lawsuits associated with even minor negative outcomes from the introduction of new products may serve to magnify the risks associated with investing in them, making companies more conservative than would otherwise be the case.

The expected payoff ratio associated with technology resource investments presumably provides an incentive for a developer which changes the productivity of the personnel engaged in the technology development process. The term ***e*** will represent the productivity enhancement factor (i.e., multiplier) associated with the value, reward, or sanction incentive for successful development.

Competition between developers

Most economists believe competition plays an important role in the innovation process. The usual assumption is that each firm attempts to minimize its own costs and expand output. Under these conditions, if a firm is not performing as efficiently as the competition, it will either lose market share or go out of business in favor of those who are more efficient. If by accident or design, a technological improvement should take place in any firm that makes it more efficient or its products cheaper or more desirable, its market share would increase, at least temporarily. Competing firms will be under pressure to adopt the same improvement, or make equivalent efficiency gains, or be driven out. Competition provides an incentive to "break out of the pack" of competitors through the establishment of an innovation-based monopoly, or a continuing incentive to innovate in order to sustain a monopoly position against the entry of potential competitors into the market. Over time, such a process leads to continuous technical improvements, even if the individual innovations occur at random. *R&D Investments with Competitive Interactions* (Miltersen and Schwartz 2004) is an example of recent research results that supports competition as an influential factor in producing technological change.

Competition that spurs technological change need not be restricted to economic competition. Harder to quantify but probably equally important are competition for individual and organizational prestige, honors, and psychological rewards.

Competition associated with technology resource development, as in the case of rewards and sanctions, presumably motivates technology developers in a way that changes the productivity of the personnel engaged in the technology development process. The symbol ***u*** will be used to represent the productivity enhancement factor (i.e., multiplier) associated with competition.

Current state of technology

When a brass device dating from 80 BC was recovered from the sea off Greece in the 1950's it was determined to be a mechanical calendar with complex gearing; a sort of calculator. It was so lacking in known predecessors in the archeological record that the discovery was likened to finding a jet plane in an ancient Egyptian pyramid. The impossibility of finding a jet plane in a pyramid makes the implicit point that the preexisting technology space matrix provides essential building blocks for subsequent technology developments. It is inconceivable that we could actually find a jet plane in a pyramid because the technology base of ancient Egypt—the technology space matrix--could not support such a development. New scientific knowledge can suggest novel and useful ways to group, combine, or make use of existing technology elements, but science and engineering can rarely if ever call forth radically new goods, services, or processes from a vacuum. Goods, services, and processes with new or increased capabilities usually result from the employment of older technologies arrayed in new ways. Even revolutionary new developments, such as the transistor seemed to be in 1947, had predecessor devices such as the solid-state diode and the vacuum tube (the vacuum tube performed functions similar to the transistor, albeit in a different way).

The importance to future technological advances of the preceding states of technology is one of the main themes in the ETEC literature:

> …"Progress" on a technological trajectory is likely to retain some cumulative features: the probability of future advances is in this case related also to the position that one (a firm or country) already occupies vis-à-vis the existing technological frontier (Dosi 1982).

The larger the effective technology element mass—i.e., numbers of technology elements in a technology space matrix, the greater is the potential that technology developers can find existing technology elements that are suitable for combining, disaggregating, sequencing or modification to transmute into new technology elements or provide stepping stones toward new technology elements. Bearing in mind that most major technological advances are the result of organized R&D efforts (Dosi 1982), the degree to which a given technology space matrix constrains or facilitates technology development can be expressed by three quantities that relate to ordinary project development steps. These three terms are:

1. The average probability of finding individual development milestones needed to complete a technology project
2. The number of development milestones that need to be accomplished
3. The average amount of resources associated with accomplishing each development milestone

Summary discussion of technology element change factors

In order to mathematically model the full impact of technological change factors on the project development process (i.e., additions to *n*) the previously developed terms for available resources, magnitude of risk-reward, and degree of competition are combined with the three terms listed immediately above which depict the technology space matrix effect on a project, i.e.:

$$n = (r*e*u) * (z^m / (m*s))$$

Where:

n = The expected number of technology element development successes [Note: it is possible for n to exceed one, indicating that with the available resources, the project can be expected to succeed more than one time on average]
r = Available resources
e = Productivity enhancement factor [i.e., multiplier] associated with the gross value or reward for successful development.
u = Productivity enhancement factor [i.e., multiplier] associated with the competition index.
z = The average probability of finding individual development milestones needed to complete a technology project
m = The number of development milestones that need to be accomplished. [Note: z^m is the probability that all development milestones for a project will be found]
s = The average amount of resources associated with accomplishing each development milestone.

This equation states that the expected number of successful technology projects increase in proportion to the resources committed (after adjustment for the productivity of those resources), but the chance of success is reduced exponentially as the number of project milestones at risk increases. The chance of success is further reduced as project costs (or milestone efforts) increase.

These results, while couched in terms of individual project development, can reasonably be expected to be upwardly scalable. If appropriately scaled, the formula can portray how the four governing factors (resources, risk/reward, competition, and existing technology state) and their interactions affect the development potential for various fields of technology, e.g., aerospace vehicles, as opposed to the a single project development like a particular aircraft design.

Factors governing changes in the diffusion of technology elements (*d*)

A survey of diffusion research cites four groups of factors that might influence diffusion, namely those that affect benefits, costs, the industry and social environment, and degree of certainty and information (Hall 2004). Basic microeconomic theory, specifically the *analysis* *of consumer equilibrium*, deals in a general way with the first two groups (benefits and costs) and makes simple assumptions (homogenous environment, perfect information) about the second two.

The analysis of consumer equilibrium concludes that the number of units bought i.e., the amount of diffusion of any good, presumably including technology elements, is found at the point at which the slope of relative marginal utilities is equal to the ratio of relative prices, adjusted for level of income. Another way of putting this is that the number of technology elements purchased or amount of use is determined partly by income and partly by how useful a technology element is compared to alternatives. The usefulness of a technology element is compared to alternatives is presumably revealed by the proportion of income technology element users devote to purchasing units of a specific technology element. These points can be summarized as follows:

$$d = \sum_{i=1}^{n} (p_i * \mathrm{I}/c_i)$$

Where:

d = Number of technology element units sold/extent of diffusion (all types)
n = Technology element type
p_i = Portion of income users on average are willing to pay for a type of technology element
I = Total income of all users
c_i = Average cost per unit of a type of technology element

The cost of production of a good normally goes down for a while as economies of mass production (i.e., scale) begin to be realized. Cost then begins to rise again as production limits are reached. Technology elements also often grow in usefulness as the number in use increase--if there are more electric cars on the road, more charging stations are likely to be provided and more experienced repairmen made available. These factors can explain the usual "S" curve pattern of a slow take-off followed by rapid growth and then a leveling off in the sales of new products and services. The cost-of-production curve and the demand (willingness-to-pay) curve together make it possible to account for changes in diffusion for technology elements as they would for any other competitively priced economic good.

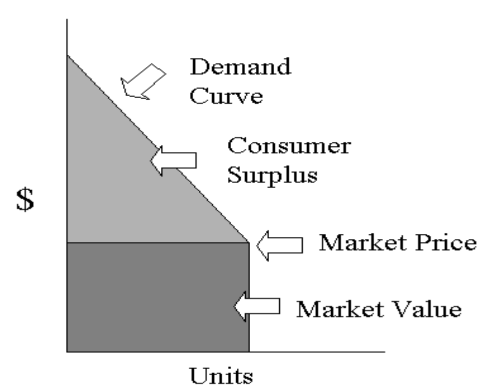
Much more sophisticated economic analysis of diffusion exists than the basic points made above. The "equilibrium models" associated with researchers Karhenas and Stoneman represent an example of such analysis. These models, based on a detailed investigation of the interaction of demand, supply, and the differing characteristics and actions of adopters, appear to have significant explanatory power relative to many aspects of the diffusion process not dealt with in this paper. Among these are diffusion process timing rates, early and late adoption patterns, the distribution of innovation benefits, the persistence of advantages from adoption, and spreading mechanisms.

Factors governing changes in the value of technology elements (*v*)

Value in technology studies has generally been treated as a part of the investigation of invention/innovation or diffusion processes in ETEC literature, and is typically included as part of the study of productivity in new growth economics. In neoclassical economics, however, the theory of utility and demand (which amounts to a theory of value) is usually considered worthy of separate and specific analysis, as it appears in basic texts such as *Economics* (Samuelson 1973). This section analyzes technology element value in the light of basic utility and demand theory.

Demand and supply sets the price (i.e., market value) of a technology element in a market setting. This is true even in the case of a patented product, so long as the patent holder tries to maximize the gain from sales of the technology element and cannot segment the market by individual purchaser. In a monopoly situation, supply will be more limited and the price consequently higher than in a purely competitive market, but demand and supply still sets the price. It is a basic assumption of demand theory that purchasers typically are willing to pay less for successive units of a good, in this case technology elements, than prior ones. Summing these individual preferences in a market results in a downward sloping demand curve.

Except for certain types of monopoly situations, a market-clearing price is always less than what everyone but the last, least motivated (i.e., marginal) purchaser is willing to pay. As a result, for practically all users there is more expected value to be gained by acquiring a good/technology element than the market price paid indicates. This excess value is known in economic theory as consumer surplus. The graphic below depicts the main factors and relationships involved in the derivation of consumer surplus, whether for technology elements or any other marketed item:



The long-run price of goods and services tends to drop from the high prices the initial buyers are willing to pay down to the cost of production due to competition. During the time it takes for competition to bring down the price to the long-run cost of production, innovators may capture much of the potential consumer surplus in the form of monopolistic or semi-monopolistic profits. The end result, however, is that the value of a technology element for most users may eventually be *much* higher than the market price paid for it. It is important to note that the creation of consumer surplus value can be thought of as *the* reason for making technology advancements from an economic and social point of view. If achieving only market value were the objective of new technology developments, there would be equally useful alternatives available at the same price. There would be no incentive either to introduce or to buy the new good or service.

The technology space matrix framework emphasizes the strong effects on technology element value that result from interactions between technology element units. This emphasis is consistent with other technology change literature. Evolutionary economic theorists frequently point to and analyze the important role of network externalities, interdependencies, and clustering of technical developments in their analyses of innovation or diffusion, all of which this paper associates with synergistic value creation. As indicated previously, new growth theorists are concerned with the productivity effects resulting from technological complementarities.

Synergistic value added by technology element interactions comes about through the formation of combinations of technology elements in whole or part, the enabling of otherwise inactive or ineffective technology elements, or complementary effects on other elements. Positive synergistic value need not result solely from high-tech technology element interactions. An example of new synergistic value arising from combinations of old technology elements is the containerization of freight. By combining truck, rail and sea transportation into a seamless transportation system by means of a low-tech metal box, the virtues of each of these three very old technologies are optimized. Transportation of goods are greatly reduced in cost and speeded up. Containerization thus achieves the functional equivalent of one or more "high-tech" advances in transportation technology. Older technologies can similarly be combined with newer ones to produce improvements.

Negative synergistic values can exist as well as positive ones. Negative synergistic effects were in evidence when the automobiles replaced the horse and buggy and thereby reduced the value of numerous horse-related technology elements. Normally, positive synergistic values can be expected to predominate over negative ones. If a technology element's synergistic value were mostly negative, there would either be no incentive for the diffusion of the new element in society, or if there were a market failure whereby market incentives did exist for the diffusion of something like a highly addictive new drug, government or other non-market mechanisms would probably act to limit its diffusion.

The number of possible combinations and other kinds of potential synergistic relationships between technology elements change much faster than does the number of technology elements in a technology space matrix. The growth in combinations and other possible synergistic relationships can be represented mathematically by factorial expansions and physically by chain reactions. If only a small portion of the rapidly growing number of potential synergistic relationships produces actual synergistic value, a rapid increase in overall technology space matrix value can result.

Synergistic values, because they are often unintended results of a complex chain of interactions between technology elements, may not be captured in the market price or consumer surplus of individual technology element units. Neither are they necessarily a value the individual user-purchaser would willingly pay for. They may be included in what economics classifies as "external" benefits or economies (or costs, diseconomies).

> …externalities are often assumed to be linked to all kinds of R&D activities (Götz 1997)

The nature, importance, and prevalence of these market imperfection effects are the subject of debate in the economic literature. Nevertheless, for many analytical purposes the correct value associated with a technology element may be what is known in economics as a shadow price—the price that takes account of all external benefits and costs.

The value of a *particular* technology element unit is equal to the sum of market price, consumer surplus and the portion of synergistic value not reflected in market value or consumer surplus. The *aggregate* value of all technology elements in a technology space matrix can be symbolized by:

$$v_T = \sum_{i=1}^{n} (v_i * d_i)$$

Where:

v_T = Total value of all technology elements
n = Technology element type
v_i = Average value of the *i*th technology element
d_i = Number of units of the *i*th technology element

The total value of all technology elements (i.e., total value of the technology space matrix) is a measure of the size and power of a technology set. Since at a high level of aggregation the sum of all technology elements in the technology space matrix is equivalent to the sum of all goods and services, v_T equates to total economic value. It does not, however, equate to gross domestic product because of the existence of consumer surpluses and shadow prices.

Conclusions

The technology space matrix framework provides a means of summarizing and evaluating technology related research in terms of just three fundamental outcomes. The framework provides researchers, managers, and policy makers with a conceptual means to monitor, synthesize and get a "birds eye" view of the vast array of information on technology change. A summary framework such as technology space matrix can provide technology insights analogous to the way an aerial photo provides insights on a geographic area, often showing large-scale relationships that might be missed if viewed close up. The technology space matrix framework can also be used as a starting point from which to identify and to "drill down" to more detailed areas of special interest.

This paper's postulated identity of all goods and services with technology implies two-way causality between economic and technology growth. Notwithstanding similar implications in some new growth economic models, such a relationship between the economy and technology is not much discussed in the technology literature. One would think that if two-way causality is valid, however, it is of great policy and planning importance. It argues for a more through integration of economic and technology policy and decision-making, activities now often seen as separate or only loosely connected.

The formula developed in the section on number of technology elements calculates the expected number of successes for technological development projects, given resource constraints and other data likely to be available or estimated during the course of developmental project planning. The components of the formula are based for the most part on recognized research and settled theory, but operation of the formula has not been tested empirically. If it can be validated by future research, such an algorithm could aid developers in making resource allocation decisions and balancing risks and costs, thereby increasing R&D efficiency.

The aggregate value of all technology elements in a technology space matrix is discussed in the section on value. Calculating an actual number for the total value of a technology space matrix presumably requires the determination of complete demand curves and shadow prices for technology elements. The practical difficulties of compiling these data may preclude total technology matrix value from being put to use in benchmarking technology change at the national level. It may, however, be practical to gather adequate data for such a calculation in the case of smaller technology matrices, e.g., particular technology segments.

The discussion of value also explains that the number of combinations/relationships between technology elements in a technology matrix can be represented by factorial expansions. In large technology space matrices, factorial-driven contributions to total matrix value made by synergistic relationships are likely to be highly significant. The great potential for synergistic value implicit in existing technology elements implies that technology policy, including public and private technology investment strategies, rather than focusing more or less exclusively on new developments, can benefit by also focusing on payoffs that can result from exploiting potential synergies between existing technology elements and between existing and newly diffusing technology elements.

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Paul Crabtree has both government and industry technology-related analytical and managerial experience. This includes staff support for U.S. congressional transportation hearings and legislation, work on environmental and habitat standards for water resources projects, benefit-cost and environmental review of hydroelectric and other construction projects, management of a large information technology organization, and nuclear plant cost analysis.

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