Technological guideposts and innovation avenues

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This paper presents an integrative view of innovation processes based on a theory of systems developed by the author over the past few years. In its essence, one of the most important clues to the origin of innovations is to be found in the fact that the performance of every technology depends upon its size and structure. Specifically, as a technology is continuously made to become larger or smaller, the relationship between its size and structural requirements changes, which in turn, severely limits the scope of its further evolution. Thus the origin of a wide variety of innovations lies in *learning* to overcome the constraints that arise from the process of *scaling* the technology under consideration. In short, technical progress is best characterized as a process of learning by scaling.

These considerations in turn point to a trilogy of innovations corresponding to three main types of technological constraints: *structural innovations* that arise from a process of differential growth whereby the parts and the whole of a system do not grow at the same rate; *material innovations* involving a change in the construction stuff; and *systems innovations* that arise from the integration of two or more *symbiotic technologies* in an attempt to simplify the outline of the overall structure. The proposed trilogy is shown to account for the emergence of various techniques including the so-called revolutionary innovations in a variety of fields.

The theory is developed and illustrated through three case studies of technical progress in the aircraft, farm tractor, and computer industries. The results of our investigation further reveal that the process of innovation is best conceived in terms of a certain topography of technological evolution. Specifically, we find that technical progress is invariably characterized by the existence of what may be called technological guideposts and innovation avenues that lay out certain definite paths of development. Chance determines which amongst many technological guideposts will be chosen in the course of development. Once the development is well along a certain innovation avenue, necessity prevails until another point connecting other technological guideposts and innovation avenues is reached. This brings chance back to the fore and the process continues. In sum, the process of technological evolution is determined by the interplay of chance and necessity rather than one at the exclusion of the other.

1. Toward an integrative view of technology

Traditionally, studies of technical change processes have varied between two extreme views. One of the earliest views used to be that technology dictates the mode of socio-economic evolution. The clearest exposition of this view is provided by Karl Marx [6, p. 92]:

> The Landmill gives you society with the feudal lord; the steam mill, society with the industrial capitalist.

Marx of course knew a great deal more about technological change than his remarks above would seem to indicate. Evidently, he was making his point by exaggeration. It was nevertheless an exaggeration that many took to their heart – including some of the most prominent social scientists of our times. William Ogburn, who laid the foundations of a whole school of sociology, confidently asserted that it is the changes in "material culture" that cause changes in "nonmaterial culture". In his own words [10, p. 85]:

> It should be no surprise to sociologists that various forms and shapes which our social institutions take and the many shifts in their function are the result of adjustments – not to a changing natural environment, not to a changing biological heritage – but adaptations to a changing technology.

In a similar vein, Joseph Schumpeter, whose work inspired a whole generation of economists, held that technical progress was an autonomous force with profound implications of an economic nature. He even foresaw the decay of capitalism resulting from the rise of monopoly power as a consequence of technological innovation [20, p. 84]:

> ... In capitalist reality as distinguished from its textbook picture, it is not (price) competition which counts but the competition from the new commodity, the new technology, the new source of supply, the new type of organization (the largest scale of unit of control for instance) – competition which commands a decisive cost or quality advantage and which strikes not at the margins of the profits and the outputs of the existing firms but at their foundations and their very lives.

By the 1950s, however, the above view of technical progress as *deus ex machina* had come under increasing criticism. It was evident that technical progress played a central role in the long term economic growth. Yet, there was no real explanation of how or why technical progress occurred in the first place. Following the result of a number of studies, it soon became apparent that the chain of causation had to be reversed. As Jacob Schmookler put it in his well-known study of the subject [19, [. 209]:

> While our ignorance may dictate the continued treatment of technological change as an exogenous variable *in our economic models,* it is plain that *in the economic system* it is primarily an endogenous variable.

It was now held that the socioeconomic evolution was a precondition rather than a result of technological progress. Thus, the intellectual history of the subject had come to a full circle.

In recent years, it has been increasingly recognized that neither of the above two extreme views of the subject is wholly justified. We need greater eclecticism in place of earlier extremism in our conception of technical change processes.

This paper presents an integrative view of technology based on a theory of evolutionary systems developed by the author over the last several years [13–17]. In its essence, technology occupies a distinct niche of its own which is best understood from within rather than exclusively from without. Viewed from the proposed standpoint, technology both shapes its socioeconomic environment and is in turn shaped by it. Neither is a sole determinant of the other; rather, the two codetermine each other.

2. The origin of innovations in morphogenesis

The point of departure of the theory advanced in this paper is the well-known observation that change in the size of an object beyond a certain point requires change in its form and structure as well [13;22]. If geometric proportions of an object are kept unchanged with change in its size, its area increases as the square and the volume as the cube of its length. Thus if the length of an object is doubled, its area is increased by four times and its volume by eight times. From a functional point of view, however, no system can endure for long if its volume is greatly in excess of its area. The reason is simple. Some of the essential properties of the system such as capacity for heat generation and weight depend upon its volume whereas other properties such as capacity for heat dissipation and strength depend upon its area. Thus a system cannot remain unchanged both geometrically and functionally with change in its size; rather, it must seek to offset the excess of its volume by selectively increasing the linear and a real dimension of its parts. In consequence, the parts and the whole of a system do not grow at the same rate. The growth of a system is generally accompanied by change in its form.

We therefore find that the basins of large rivers tend to be proportionately longer as compared to those of small streams. This is because the length of the river's main channel disproportionately increases with increase in its drainage area. Likewise, large ships are characterized by proportionately smaller beam length. In an essentially similar way, small plants tend to be more slender compared with large trees. Moreover, large trees branch proportionately more as compared with small plants so as to maintain a certain parity between their surface area and the volume. So, also, large bridges cannot hold without the support of exceptionally heavy girders. Similarly, large wheels require proportionately fatter tires as is particularly evident in some sports cars. Often a system cannot survive if its size is continuously changed without a concomitant change in its shape.

We are therefore assured that contrary to the narrative of Jack the Giant Killer, Jack had no reason to be afraid of the giant [22]. If the giant were ten times as large as an average man, and had similar proportions, he would indeed be a weakling at best. This is because his weight would be a thousand times that of the average man. However, the cross-sections of his bones would be only a hundred times those of the average man so that every square inch of his bone had to support ten times the weight withstood by a square inch of the average man's bone. Chances were that the giant could not walk one step without fracturing his thighs. Jack had every reason to feel perfectly safe and sound.

More generally, the form of a system must be appropriate to its size. In consequence, we find that the observed variety of forms is often more apparent than real. To take one among many examples, Gothic architecture characterized by flying buttresses along with ribbed vaulting and the pointed arch is easily distinguishable from the classical and renaissance architecture characterized by the solid wall exhibiting regular windows. We are told that the origin of Gothic form lay in the mystical spirit whereas the origin of the classical and renaissance form lay in the materialistic spirit of the day. It is equally true, however, that the characteristic elements of both architectural forms are attributable to the necessity of transferring the weight of the structure to the ground while attempting to increase its overall size.

Frequently, change in the size of an object also necessitates change in the material employed in its construction. Thus it is often necessary to use special heat-resistant alloys in constructing the blades of large turbines. The current R&D effort to develop single crystals of the nickel chromium super alloys in making new blades for jet engine turbines is a case in point. So, also, it is essential to insert steel rods in casting the large concrete beams. Such provisions are unnecessary for small objects. One other way to overcome the adverse effect of change in the size of an object is to eliminate unnecessary material in its construction. Thus it is commonplace to use large steel beams in the "I" form so as to conserve their strength for supporting the weight of the structure under consideration.

Finally, change in the size of an object often introduces various complications in its structure. Thus large organisms cannot survive without increased differentiation of functions leading to the development of a respiratory mechanism because the quantity of respiratory tissues varies as the cube, whereas the surface of gas exchange varies as the square, of linear dimensions. Small organisms, on the other hand, can do without gills or lungs, because gas exchange can occur fast enough for metabolism by means of diffusion alone. Similarly, large turbogenerators need specialized insulation devices because the volts per turn on each coil quadruples, whereas the thickness of the turn-to-turn insulation only doubles with the doubling of linear dimensions. Larger transformers also require complicated methods of cooling in the form of additional fins, coolant pumps and fans because heat generation varies as the cube, whereas heat dissipation varies as the square, of linear dimensions. Such complications are unnecessary for small devices.

Thus, change in the size of a system is generally accompanied by differential growth of its components in relation to the whole, change in the materials of construction and increase in the complexity of its structure. However, these processes cannot continue indefinitely without degenerating into absurdities. In consequence, there is a limit to the growth of every system of a given form. The story has it that the tower of Babel was never completed because divinity, concerned by the prospects of intrusion, put words in the mouths of builders that no one could understand. A more likely reason for the apparent failure of the mission would seem to lie in the vast dimensions of the proposed structure. Similarly, in modern times, we find that the height of the fractionation towers for petroleum refining is limited by the exceptionally heavy supports required for the distillation tray. So, also, the miniaturization of electronic devices is limited by the complexity of interconnections between the components. In essence, the very processes that initiate the evolution of a system eventually limit its future evolution. It is therefore to be expected that for any given form of the system, the range of appropriate sizes is limited.

The thesis is advanced here that one of the most important clues to understanding the process of innovation is to be found in the web of links between the functional performance of a technology and its size and structure. Thus, it is conceivable that the origin of innovations lies in *learning* to overcome the constraints that arise from the process of *scaling* the technology under consideration.[1] In short, technological evolution is best

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[1] A consideration of some of the related issues will be found in earlier works of the author [13–16].

characterized as a process of learning by scaling.

Specifically, three major types of innovations may be identified on the basis of technological constraints noted above. First, we have what may be called *structural innovations* that arise out of the process of differential growth whereby the parts and the whole of a system do not grow at the same rate. Second, we have what may be called the *material innovations* that are necessitated in an attempt to meet the requisite changes in the criteria of technological construction as a consequence of changes in the scale of the object. Finally, we have what may be called the *systems innovations* that arise from integration of two or more *symbiotic technologies* in an attempt to simplify the outline of the overall structure. The distinction between the three categories of innovations is relative rather than absolute. As discussed below, their origin can be invariably traced to the simple fact that a technology can properly function only for a particular combination of size and structure.

3. A metaevolutionary explanation of revolutionary innovations

Two features of technological progress stand out above all others. First, economies of scale have played a prominent role in the innovative activity across a wide variety of fields. We find therefore that aircraft have become progressively larger whereas electronic devices have become progressively smaller in size over the course of time.[2] Second, however, a close examination of the evidence reveals that the basic form of the key technique within any given field has remained unchanged over long periods of time. Thus, *a priori*, according to the theory advanced here, it may be inferred that the origin of a wide variety of innovations lies in certain natural limitations to the evolution of technology discussed above. The point seems to be one of great generality. John Locke once remarked that it is of great use to the sailor to know the length of his line, though he cannot with it fathom all the depths of the ocean. This is likewise true of technical explorations: the knowledge of constraints is of paramount importance. We find therefore that innovations depend upon the coexistence of certain developing as well as limiting processes.[3] The following case studies of technical progress may help make this clear.

3.1. Technical progress in the aircraft industry

It is often claimed that the introduction of DC-3 aircraft in 1936 marked the beginning of a new era in the development of technology. This is certainly borne out by the evidence. The DC-3 was a product of a great deal of prior development effort. In turn, it became a focal point of significant further development of technology. Thus it is noteworthy that the essential features of the DC-6 introduced in 1951 were identical with those of DC-3. The difference between the two lay in the degree of refinement rather than in the kind of design. Individually, these refinements were of a minor nature. Collectively, however, they had a major impact on the capability of technology. As Miller and Sawers put it [7, p. 128]:

> What did not happen to airliner design is more interesting than what did in the quarter-century between the introduction of the DC-2 and that of the big jets in 1958. Airliners changed from the DC-2 mostly in size, number of engines and power; and these alterations sufficed to increase their cruising speed from 170 m.p.h. to 310–330 m.p.h. and their range with capacity payload from 600 miles to 4760 miles ... The enormous growth in air travel between the 1930's and 1950's was not the result of any great improvement in the design of the airliner, though it was helped by its higher speed and longer range which made international air travel practical. All the efficiency that made the airliner a cheap enough means of travel to attract passengers in a significant number depended on the innovations of the early 1930's.

Thus, while the essential form of the aircraft design remained unchanged, the sale of technology significantly increased during the time period from 1936 to 1948 (see fig. 1). As a consequence, the

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[2] As Nelson and Winter note [8], the phenomenon of continual changes in the scale of technology is sufficiently general to warrant the status of a natural trajectory. See also an excellent paper by Dosi [3] which presents a somewhat similar viewpoint.

[3] As discussed elsewhere by the author [14], this is true not only in technological but in organizational and social innovations as well.

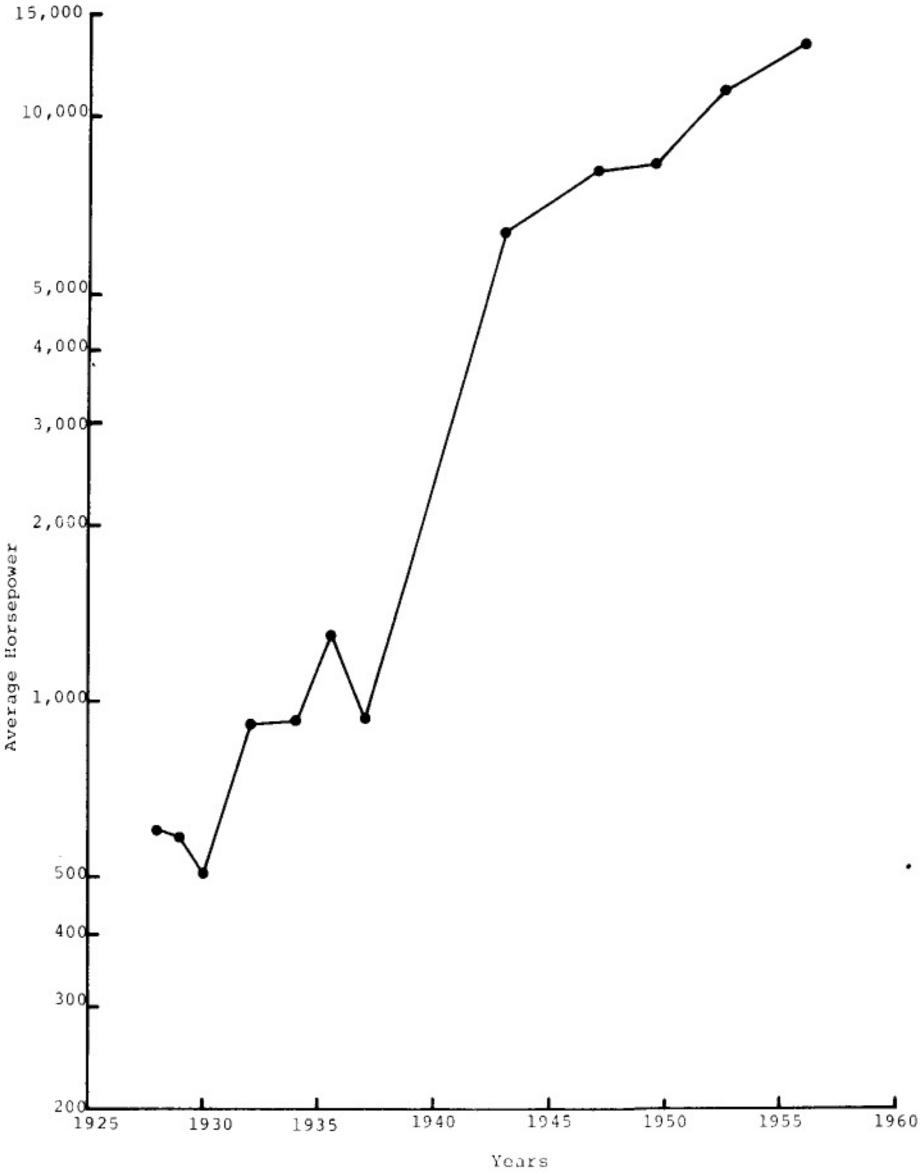

Fig. 1. Growth in the size of aircraft technology.

combination of piston engine and propeller had reached the limit of its performance by the late 1940s. One main constraint to technical progress lay in the fact that propellers became increasingly noisy and inefficient as their tips approached the speed of sound which in turn restricted the maximum speed of the aircraft. Further advances in technology were also limited by metal fatigue resulting from high vibrations as a consequence of increase in the engine power over the course of time. Thus, both the speed and power-to-weight ratio of the piston engine aircraft had peaked out at levels that were much too low for supersonic flight. It was essential to try out the hitherto dormant jet engine to find a way out of the impasse.

The jet aircraft was first successfully flown as early as 1939. However, the use of the jet engine in aircraft was beset by a number of problems. Its range was limited by its high fuel consumption. Its reliability was uncertain because of the use of new alloys and high temperatures at which it operated.

Its capability to develop thrust at low speed was restricted. The jet engine did have one basic merit: it was relatively light and compact. The fuel consumption of jet aircraft was gradually reduced with the development of axial flow compressors from 1948 to 1957. Its power and efficiency were further improved by the installation of a fan type engine in the early 1960s and then by gradually raising the bypass ratio (the proportion of air that passes through only the fan). Together these developments ensured the dominance of the jet powered airliner as the most economical means of transportation for flights of more than 200 miles carrying 50 or more passengers. The jet engine was of course a truly pathbreaking innovation. What is significant for the purpose of the present study is that its importance lay in the fact that it was a systems innovation: it simplified the form of aircraft design – inasmuch as it was based on a rotating rather than a reciprocating mechanism – thereby circumventing the constraint to further development of technology.

A number of other important advances in aircraft technology are demonstrably attributable to material innovations. Thus, a great deal of progress in the airframe technology has been made possible by development of new materials such as duralumin and various other aluminium alloys that are as light as possible and yet strong enough to withstand various stresses in the course of flight. Similarly, advances in engine technology have come not only through development of improved fuels but also through continuous search of metals that are both light and can withstand high temperatures and pressure. Thus the development of the jet aircraft was in no small measure made possible by the development of titanium-based alloys that could withstand higher temperatures than aluminium. Likewise, the installation of a fan type of engine in the jet aircraft was largely made possible by improved alloys. Moreover, major technical advances in the future are expected to come from substitution of composite materials for aluminium alloys in airframe construction and from the development of heat resistant turbine blades. Two alternative approaches are being pursued towards the development of these new blades. The first approach seeks to make the blades from a single crystal of an alloy so as to avoid the boundaries between grains of metal which often cause fatigue. The second approach attempts to orient the grains in a common direction during the production process. Further advances in the performance of jet aircraft hinge upon the outcome of these efforts.

Finally, yet other advances in aircraft technology have been made possible by various structural innovations. As a prime example of this we find that the transition from the space frame to monocoque or single shell construction in 1930s was dictated by the sheer increase in the aircraft load and speed resulting from increase in the scale of technology. The swept wings were likewise an outcome of the attempts to circumvent the constraint posed by increase in the fatigue as a result of increase in the engine power.

3.2. Technical progress in the farm tractor industry

It is generally agreed that the introduction of the Fordson and Farmall models during 1917–1926 touched off a whole series of technical advances in the farm tractor industry. The Fordson was a product of the assembly line while inaugurating the frameless type of design. Its low cost of production was an important spur to widespread diffusion of technology. The Farmall was the first general purpose tractor rather than just a plowing machine. Its adaptability made it possible to utilize the tractor for a wide variety of farm operations including harvesting. Together, these two models marked the emergence of a basic pattern of tractor design that has remained intact to this day except for numerous refinements. As Reece put it [12, p. 125]:

> Tractor production throughout the world has settled down into a small number of distinct tractor forms, skid-steered track layers, toolframe tractors, and the conventional two-wheel (2 W.D.) machine and its four wheel drive (4 W.D.) variants ... production is ... totally dominated by the rigid frame, 2 W.D. tractors with a small proportion of 4 W.D. adaptations. This form of tractor was first introduced by Ford in 1917 .... Since then great progress has been made in detailed design and the machine has become much more complex, but no further really significant changes have occurred.

Similarly, in the view of one industry spokesman [4, p. 9]:

> The Farmall has undergone many changes in power and utility since it was introduced. Though each year has seen important refinements, the essential features have remained the same.

It is noteworthy that the basic pattern of tractor design was a culminating point of a series of development efforts ranging well over a decade. Its very consolidation also made it a starting point for a great many further technical changes via a process of incremental changes and increases in the scale of technology (see fig. 2). However, the phenomenal increase in tractor power along with endless modifications of an essentially one and the same pattern of design also made the technology so complicated that by late 1930s it was no longer possible to further improve its performance. Clearly, a limit to technological development had been reached. This necessitated the development of three point linkage for control of integrated implements so as to overcome the constraint to further evolution of technology.

An integral tractor plow supported by a three point hitch was originally developed as early as 1917. This was perfected into a combined system of linkage and hydraulic control in 1935. The Ferguson system, as it came to be called, was undoubtedly an outstanding innovation. Its importance lay in the fact that it was a systems innovation: it simplified the pattern of tractor design in its entirety by streamlining the combined tractor implement system, thereby circumventing the constraint to further development of the technology.

The origin of a number of other important advances in tractor technology clearly lies in material innovations. The reliability of the tractor in the infant stage of its development was much improved by the development of hardened alloy-steel bevel gears. The success of the Fordson trac-

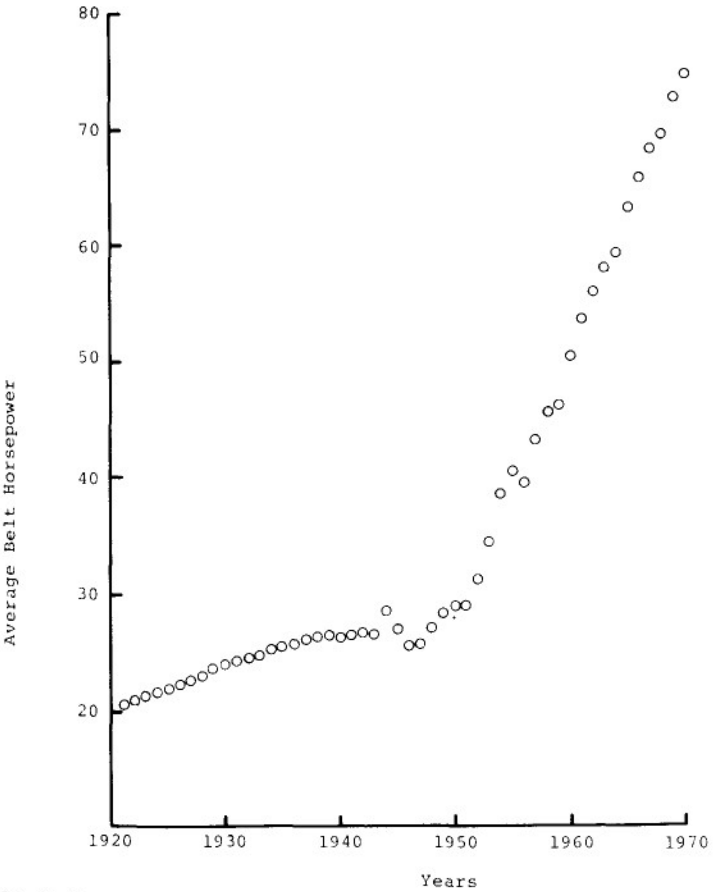

Fig. 2. Growth in the scale of farm tractor technology.

tor was in no small part made possible by the substitution of cast iron for boiler plate steel. One important source of improvement in the modern day tractor engine is to be found in the substitution of aluminium for cast iron in the construction of pistons. A wide variety of other technical advances are demonstrably attributable to various advances in metallurgical techniques such as alloy and deep drawing forging, heat treating practices, and gear manufacturing and testing devices.

Finally, structural innovations have played a significant role in enhancing the capability of the technology. The substitution of rubber tires for steel wheels in farm tractors is an important case in point. It was largely made possible by the differential reduction in the size of the drive wheels in relation to the overall tractor size over several years. The introduction of dual rear wheels and the adoption of the four-wheel drive were similarly an outcome of the attempts to increase drawbar pull under adverse soil conditions with increase in tractor size over the course of time.

3.3. Technical change in the computer industry

It is commonly recognized that the notion of a mechanical device capable of performing arithmetic operations in a digital manner dates back to the time of Pascal and Leibniz in the seventeenth century. It is also widely agreed that one milestone in technical progress was the "analytical engine" (a general purpose machine) conceived and designed by Charles Babbage during 1823–1871. However, what is often overlooked is that the analytic engine marked the emergence of a certain basic form of computer design that has persisted to this day except for numerous refinements. According to one careful account of the genesis of modern day computer technology [18, p. 1042]:

> Babbage's design had all the elements of a modern general-purpose digital computer; namely: memory, control, arithmetic unit, and input/output. The memory was to hold 1,000 words of 50 digits each, all in counting wheels. Control was to be by means of sequences of Jacquard punched cards. The very important ability to modify the course of a calculation according to the intermediate results obtained – now called conditional branching – was to be incorporated in the form of a procedure for skipping forward or backward a specified number of cards. As in modern computer practice, the branch was to be performed or not depending upon the algebraic sign of a designated number. The arithmetic unit, Babbage supposed, would perform addition or subtraction in one second while a 50 × 50 multiplication would take about one minute. Babbage spent many years developing a mechanical method of achieving simultaneous propagation of carries during addition to eliminate the need for fifty successive carry cycles. Input to the machine was to be by individual punched cards and manual setting of the memory counters; output was to be punched cards, printed copy, or stereotype molds. When random access to a table of functions – stored on cards – was required, the machine would ring a bell and display the identity of the card needed.

The major headway in the construction of computers of course had to wait until 1944 when an electromechanical computing machine called Mark I was successfully made operational. Even so, Babbage's design had left a lasting imprint on the shape of the technology to come. As Howard Aiken, the leader of the team that built Mark I, reportedly put it: "If Babbage had lived 75 years later, I would have been out of a job." A number of successful electronic digital computers soon followed.

By the late 1940s the technology had reached the limit of its performance. One main obstacle to further technical progress lay in the fact that vacuum tubes generated prodigious amounts of heat which in turn limited their reliability and operating life. The constraint was of course particularly severe in the case of large systems. For example, the first electronic computer ENIAC developed in 1945 contained nearly 18,000 tubes. It represented something of the state of the art. Larger systems were infeasible because of the prohibitive amount of time required to detect and replace the defective tubes. Moreover, the design of vacuum tubes prohibited reductions in size and cost.

By the same token it was apparent that the capability of computers could be significantly improved if the constituent elements of technology could be made smaller. Obviously, electric pulses would have to traverse shorter distances, thereby making it possible to increase the number of oper-

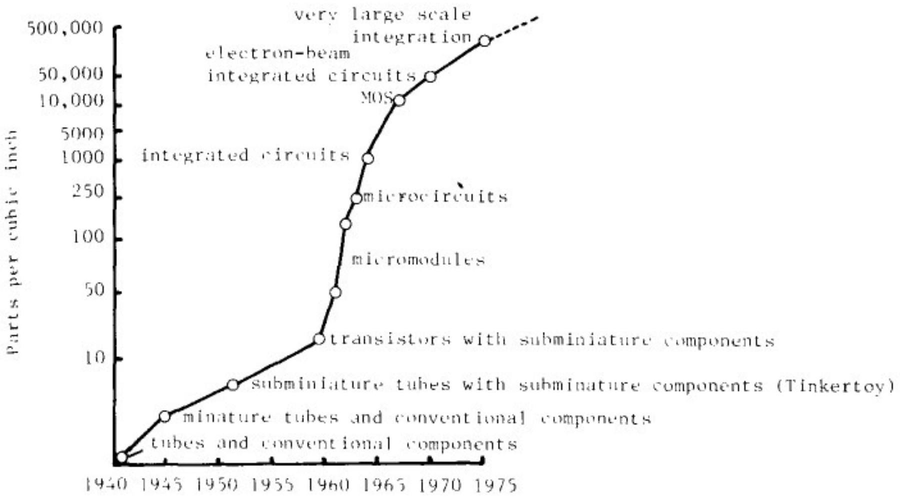

Fig. 3. Miniaturization of electronic devices (Braun and MacDonald, 1978).

ations per unit of time. Thus a series of efforts got underway to substitute the transistor for vacuum tubes in computers. These attempts also marked the emergence of a trend toward miniaturization of electronic devices that was to continue to this day (see fig. 3).

The transistor was invented in 1948 but its initial capability was distinctly inferior to that of the valve. Not only that the frequency performance of the transistor was more restricted, it was far less reliable in comparison with the vacuum tube. It was not any easy task to design a transistor to provide the requisite characteristics. Moreover, it was especially difficult to produce transistors of uniform characteristics. These obstacles could only be gradually overcome.

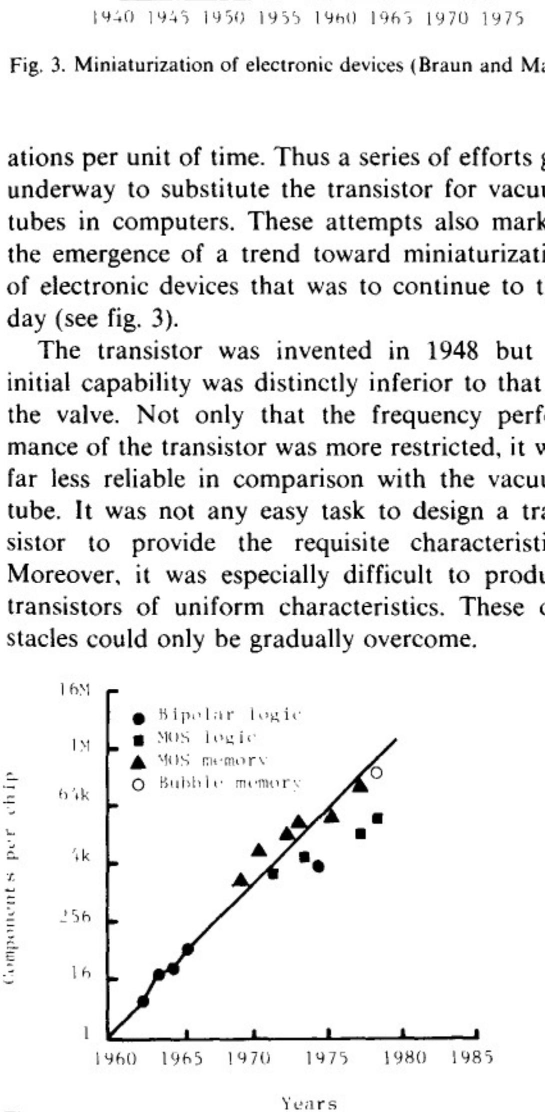

Fig. 4. Growth in the complexity of semiconductor devices (Noyce, 1977).

In 1950 Western Electric developed the technique of single crystal growing consisting of a new method of growing and doping germanium crystals. This made it possible to increase the yield in the production of transistors while increasing their resistance to shock. Two years later, General Electric developed the so-called alloy process which in turn made it possible to significantly improve the switching capabilities of the transistor. In 1953 Philco devised the technique of jet etching leading to the development of surface barrier transistors in the following year. Together these developments paved the way to increase the frequency range and switching speeds of the transistor. Soon thereafter, transistors had virtually displaced vacuum tubes in nearly all types of computers.

By the early 1960s the discrete semiconductor devices had reached the limit of their performance just as the vacuum tubes had reached the peak of their capability a decade earlier. One main obstacle to technical progress lay in the fact that the chances of system failure greatly increased with the increase in the number of interconnections between components. In essence, the problem was one of a tyranny of numbers. Clearly, the trend toward increasing complexity of technology had acquired a firm hold (see fig. 4). Thus reliability became a significant obstacle – a systematic hurdle that could not be overcome merely through improving the reliability of individual components. One way to surmount this "tyranny of numbers" lay in the application of the integrated circuit invented by Texas Instruments in 1958.

The integrated circuit was clearly an outcome of much prior research and development effort spanning over a decade. Even so, it was beset by a number of problems. In particular, it lacked a suitable means of production. This limitation was overcome with the development of planar process by Fairchild in 1960, itself an outgrowth of the older process of oxide masking and diffusion devised by Western Electric in 1955. The prospects for the integrated circuits nevertheless remained limited by the problem of poor production yields up to mid-1960s. One solution to this problem lay in the discovery by Motorola that yields could be improved by a factor of as much as four by reducing wafer area to one fourth of its earlier size because wafer defects were not distributed in a random fashion. By 1970 it became possible to devise an MOS (Metal Oxide Semiconductor) integrated circuit. This made it possible to put an even greater number of circuits on a single piece of silicon because it required much less power than the earlier bipolar integrated circuit. In the following year it became possible to place the entire central processing unit of a computer on a single chip of silicon leading to the successful development of the microprocessor. The age of very large scale integration had begun.

In retrospect, it is widely agreed that the transistor, integrated circuit and microprocessor were momentous innovations. What is noteworthy for the purpose of the present study is that they were systems innovations: their importance lay in the fact that they made it possible to progressively streamline the structure of technology, thereby paving the way for the truly phenomenal advances in the capability of computer (and other) technologies. Moreover, it is evident that the advances in computer technology have been intimately linked with the advances in the material sciences.

In the future, systems and material innovations are likely to play an even more important role in technical progress. One indication is provided by the very high speed integrated circuit (VHIC) program undertaken by the U.S. Department of Defense [5]. Briefly, the program seeks to reduce the size of semiconductor devices by a factor of 4:1 from 5 μm feature size to 1.25 μm feature size (i.e. circuit line width drawn on a single piece of silicon chip) in its initial phase. However, there are a number of constraints to meeting the proposed objective. Note that both the device density and resistance of interconnection between components increase, whereas device current and voltage decrease, as the square of the scale reduction factor. Thus, if the goal is met, it should be possible to construct devices that consume only 1/16th as much power as current devices but are nearly 16 times as complex as the current technology. The resulting increase in current density raises numerous problems of its own such as electromigration of motion of atoms induced by current in metallic wires and difficulty of heat removal. Both systems and material innovations will be needed to overcome the spending constraints. Thus it may be necessary to develop new circuit forms such as the Josephson junction (to circumvent the cooling problem) as well as new compound materials such as gallium arsenide (to overcome the electromigration problem).

Three conclusions emerge from the above case analyses. First, the theory accounts for a wide variety of technical advances in terms of the proposed trilogy of structural, material, and systems innovations.

Second, it is commonly said that certain innovations such as the jet engine, the three point hitch and control system, and the modern electronic computer constitute revolutionary breakthroughs. While this viewpoint is obviously correct as far as it goes, it is both vacuous and a mere *petito principi*. Both from a theoretical and policy point of view, the crucial question is: what determines the occurrence of revolutionary breakthroughs? If the considerations advanced here are any guide, the origin of *revolutionary innovations* lies in certain *metaevolutionary processes* involving a combination of two or more *symbiotic technologies* whereby the structure of the integrated system is drastically simplified. Thus the advent of the jet engine lay in the combination of jet propulsion and gas turbine. The three point hitch and control system originated in an attempt to integrate the farm tractor and implement technology. The electronic computer resulted from a marriage of the programmable calculating machine and solid state technology. This is likewise true of the radical process innovation. Thus the development of the planar process was made possible by blending the techniques of diffusion and chemical etching, and photolithography originally developed for printing purposes.

Third, it is apparent that the innovation process in a wide variety of fields is governed by a common system of evolution. Typically, the process of technological development within any given field leads to the formation of a certain pattern of design. The pattern in turn guides the subsequent steps in the process of technological development. Thus innovations generally depend upon bit-by-bit modification of an essentially invariant pattern of design. This basic design is in the nature of a *technological guidepost* charting the course of innovative activity. [4]

There is an important corollary to the above proposition. It is that technical advances do not take place in a haphazard fashion. Rather, they are expected to occur in a systematic manner on what may be called *innovation avenues* that designate various distinct pathways of evolution. We may say that the technological guideposts point to the innovation avenues just as the innovation avenues lead to technological guideposts. In what follows, we will attempt to determine if the process of innovation is in fact canalized as indicated by the theory.

4. Invariant factors in innovation processes

In order to test the hypothesis of innovation avenues, two issues must be addressed. First, it needs to be ascertained whether there in fact exists a stable relationship between the performance and the scale of any given technology over the course of time. Second, and more importantly, it is imperative to determine whether these relationships in turn imply the existence of some invariant factors in the evolution of technology. [5]

The notion of an invariant factor may be formalized as follows. Consider the flow of a viscous fluid through the tube governed by the well-known Poiseuille law $J = (\pi/8)\ (Pr^4/\eta)$, where J is the volume flow rate of the fluid, P the pressure gradient, r the radius and η the viscosity. The dimensions of J, P, r, and η are L^3T^{-1}, $ML^{-2}T^{-2}$, L, and $ML^{-1}T^{-1}$, respectively, where M, L, and T denote the dimensions of mass, length, and time, respectively. The parameter η is illustrative of a *dimensional constant* that appears in many physical laws. Specifically, it is a *system dependent constant* whose value uniquely characterizes any given system. By the same token, its value systematically differs for different systems even under a fixed set of scales of measurement. A more general type of a dimensional constant is a *universal constant* such as the speed of light whose value is always observed to be the same for a fixed set of scales of measurement. Note, moreover, that the dimensions of the both sides of Poiseuille's equation are exactly the same, i.e., L^3T^{-1}. The equation is therefore dimensionally homogeneous, i.e. it is invariant under the scale change transformation $x' = Kx$ where x is a general variable and K an arbitrary constant.

it is well known that a dimensionally homogeneous equation can always be reformulated in terms of dimensionless products. Thus Poiseuille's law can be equally well expressed in terms of the following dimensionless product:

$$\Pi = J\eta P^{-1}r^{-4}$$

it can be readily verified that Π is dimensionless because it is given by $M^0L^0T^0$. In essence, it is a criterion of similarity in comparing the flows of two or more viscous fluids.

The example as a whole points to a very general proposition: the existence of a law necessarily implies the existence of certain dimensional constants and dimensionless numbers which together constitute the invariant properties of the system.

In the light of the above considerations, the essence of our theoretical investigation can be very simply put forth. It is an attempt to determine what, if any, dimensional constants and dimensionless numbers can be found to characterize the evolution of technology. Clearly, if any dimensional constants and dimensionless numbers can be found, and if the data prove that they in fact remain relatively constant or vary within a limited range despite changes in the scale of technology, it can be justifiably concluded that technical progress is governed by an *inner* logic or law of its own. [6]

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[4] A further discussion of the concept of a technological guidepost can be found in earlier works of the author [13].

[5] The following exposition of an invariant factor is deliberately made as simple as possible. The specific methodology employed here was originally developed by Stahl [21]. A rigorous treatment of the concept of an invariant factor in evolution will be found in an earlier work of the author [13].

[6] In a fundamental sense, such a law of technical progress is illustrative of a very general principle of self-resemblance proposed elsewhere by the author [13]. It is well described by the ancient adage that the more an object changes the more it remains the same.

Table 1
The process of learning by scaling in the evolution of aircraft technology, 1928–1957 [a]

Dependent variable (Y)	Independent variable (W)	Estimated relationships	R^2	S
1. Average horsepower	Average gross take-off weight (lb)	$\log Y = -2.78 + 1.039 \log W$ (0.17) (0.016)	0.99	0.07
2. Average wing-loading (pounds per square foot)	Average gross take-off weight (lb)	$\log Y = -2.05 + 0.542 \log W$ (0.31) (0.03)	0.97	0.13
3. Cruise speed (miles per hour)	Average gross take-off weight (lb)	$\log Y = 2.37 + 0.293 \log W$ (0.35) (0.03)	0.88	0.14
4. Service ceiling ($\times 1000$ miles)	Average gross take-off weight (lb)	$\log Y = 1.74 + 0.133 \log W$ (0.22) (0.02)	0.79	0.09
5. Normal full load cruise range (miles)	Average gross take-off weight (lb)	$\log Y = 1.351 + 0.564 \log W$ (0.50) (0.04)	0.93	0.21
6. No. of engines	Average gross take-off weight (lb)	$\log Y = -2.32 - 0.314 \log W$ (0.31) (0.03)	0.91	0.13
7. Initial climb rate	Average gross take-off weight (lb)	$\log Y = 6.61 + 0.04 \log W$ (0.29) (0.02)	0.19	0.12
8. Passenger capacity	Average gross take-off weight (lb)	$\log Y = -5.35 + 0.822 \log W$ (0.19) (0.02)	0.99	0.07
9. Empty weight in (lb)	Average gross take-off weight (lb)	$\log Y = -0.17 + 0.968 \log W$ (0.15) (0.01)	0.99	0.06

[a] *Definitions:* R^2 is the coefficient of determination and S is the standard error of the estimate. Standard errors of the coefficients are indicated in parentheses.
Source of data: Sahal [17].

The first case examined here is the evolution of aircraft technology during the time period 1928–1957. Several measures of technical progress are considered including changes in both performance variables (e.g. horsepower, cruise speed, and passenger capacity) as well as design variables (e.g. wing loading and number of engines). The scale of technology is measured in terms of gross take-off weight of the aircraft in pounds. The parametric estimates of the relationships between chosen measures of technology and its scale are presented here in table 1. The explanatory power of these relationships is generally excellent as indicted by coefficients of determination. This is further illustrated here in figs. 5–10. It can be seen that there exist highly stable patterns of technological evolution. The results also indicate that the evolution of aircraft technology is accompanied by a process of *differential growth* of its various dimensions. We find therefore that the increase in the passenger capacity has been proportionately smaller than the increase in the overall scale of technology (eq. 8, table 1). In turn, this had made it possible for complexity of technology measured in terms of number of engines to increase at an even pace in relation to increase in the linear dimensions of the system [eq. 6, table 1]. In conclusion, it may be said that a wide variety of advances in aircraft technology are demonstrably attributable to the process of learning by scaling.

A number of dimensionless products and dimensional constants based on the variables under consideration are presented in table 2. The data in table 1 confirm that they are virtually independent of the scale of the technology. The conclusion to be drawn is that the evolution of aircraft technology has, in fact, been characterized by the existence of certain invariant factors. This may be further illustrated by means of the following examples.

The first invariant factor (I_1) listed in table 2 is the ratio of cruise range to wing loading with a numerical value of 29.98. For the 10,130 lb Ford Trimotor model 4-AT-E introduced in 1929 we obtain a value of $I_1 = 43.41$; for the 100,000 lb DC-6B introduced in 1951 we obtain a value of $I_1 = 40.93$, notwithstanding the gross take-off weight ratio of nearly 10:1. Thus the invariant

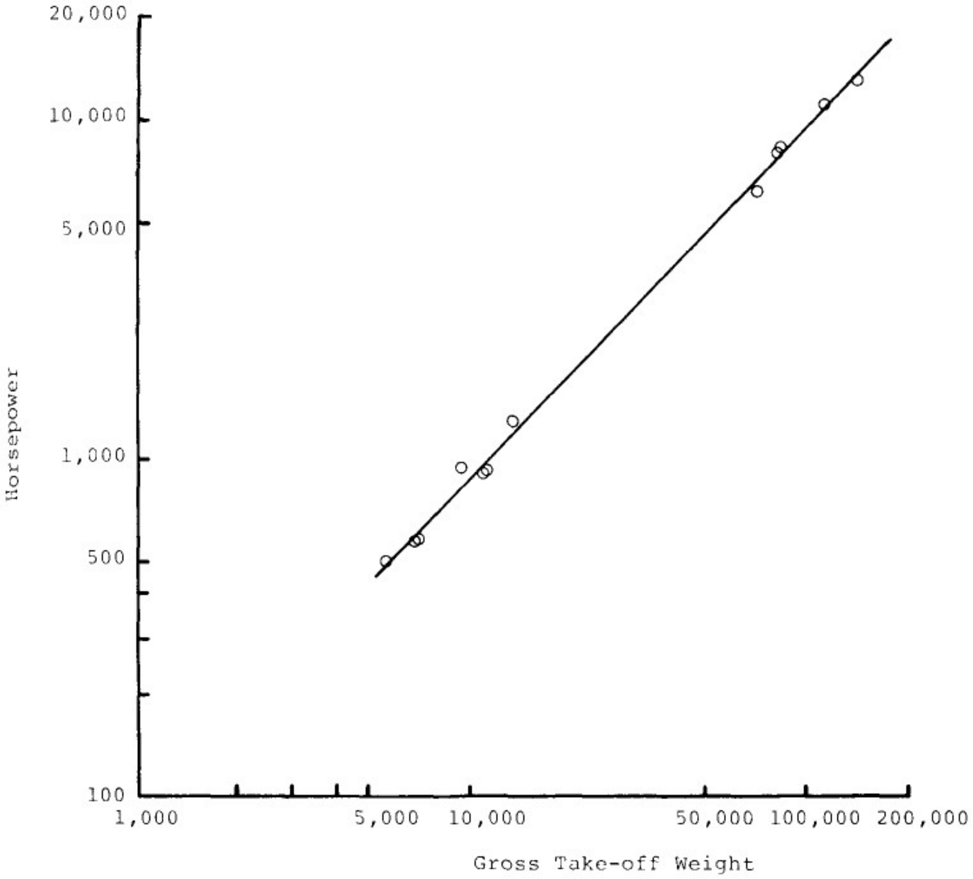

Fig. 5. Relationship between horsepower and size of aircraft, 1928–1957.

factor I_1 is practically constant across a wide variety of aircraft models; the small variation in its value is attributable to the weak scale effect as indicted by its associated residual scale exponent value of 0.02. Interestingly, Boeing 707-120 with a weight of 258,000 1b at the time of its introduction in 1958 turns out to have a value of $I_1 = 28.30$ which is remarkably close to the representative

Fig. 6. Relationship between wing loading and size of aircraft, 1928–1957.

Fig. 7. Relationship between cruise speed and size of aircraft, 1928–1957.

numerical value of $I_1 = 29.98$ given in table 2 even though it was not included in our original sample. In essence, it would be possible to predict the advent of jet aircraft by means of the proposed theoretical concepts.

As a second example consider the invariant factor (I_5) listed in table 2, specified as (wing loading × cruise range)/(passenger capacity × cruise speed). For the Ford Trimotor, $I_5 = 5.47$; for the DC-6B, $I_5 = 9.18$; and for the Boeing 707, $I_5 = 4.08$, despite the tremendous differences in the scale of technology. The remaining invariant

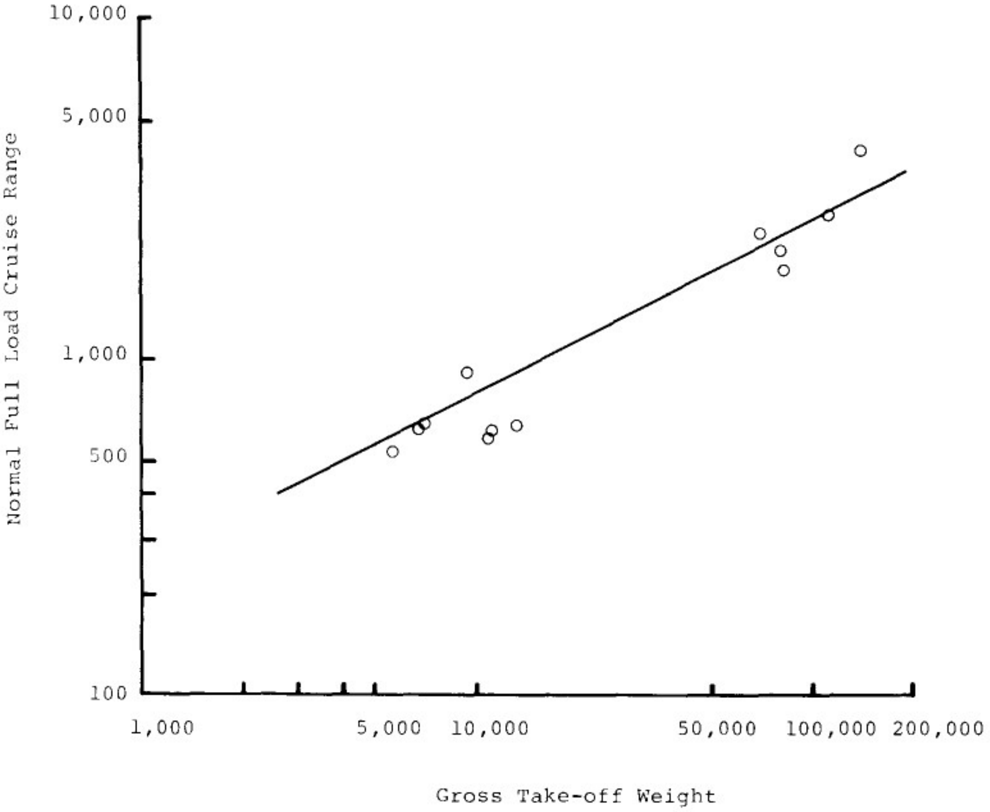

Fig. 8. Relationship between range and size of aircraft, 1928–1957.

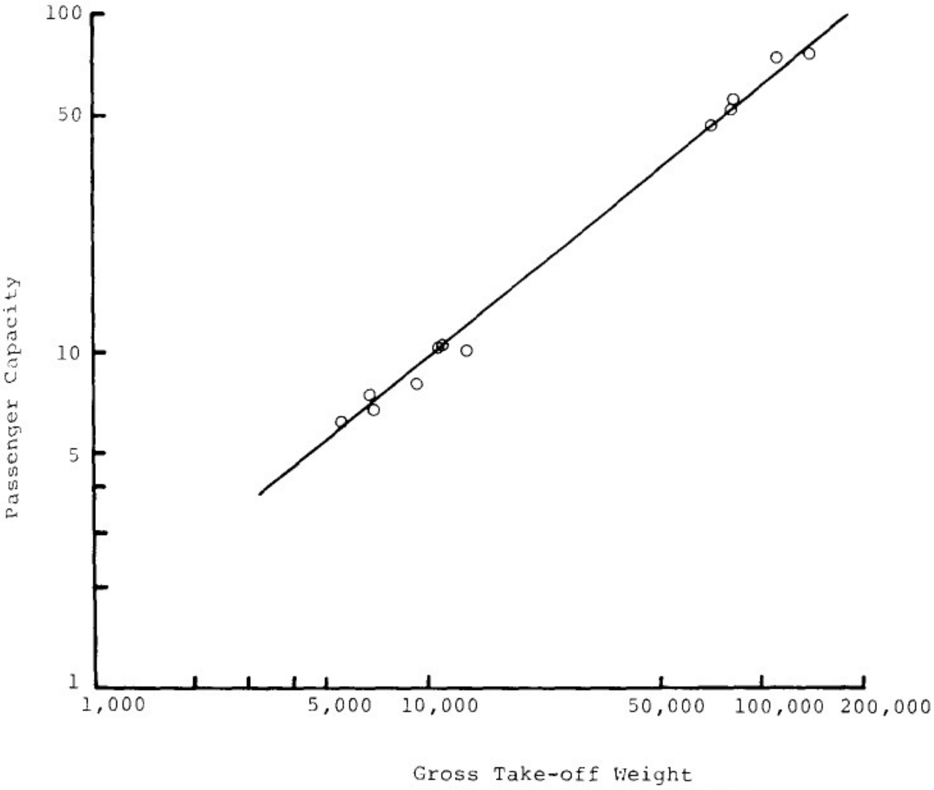

Fig. 9. Relationship between passenger capacity and weight of aircraft, 1928-1957.

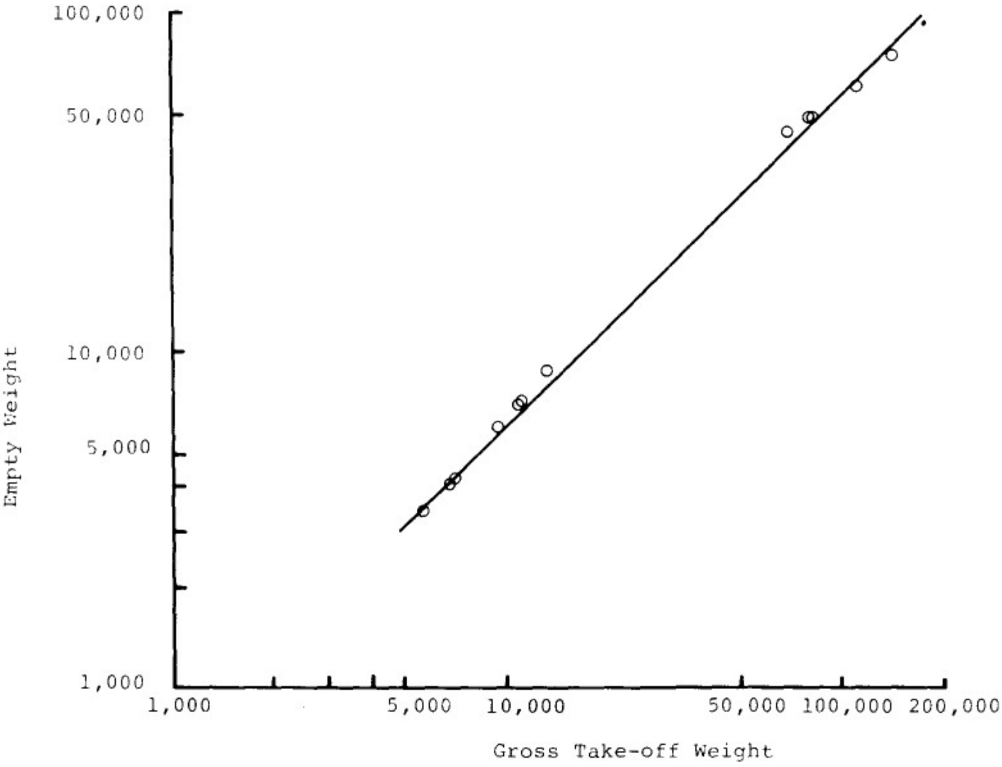

Fig. 10. Relationship between empty weight and gross take-off weight of aircraft, 1928-1957.

Table 2
Invariant factors in the evolution of aircraft technology

Invariant	Composition	Scaling laws	Resulting parameter	Residual scale exponent
I_1	$\frac{\text{Cruise range}}{\text{Wing loading}}$	$\frac{3.86(W)^{0.564}}{0.128(W)^{0.542}}$	29.98	0.02
I_2	$\frac{\text{Climb rate} \times \text{empty weight}}{\text{Horsepower}}$	$\frac{742.48(W)^{0.04} \times 0.84(W)^{0.968}}{0.06(W)^{1.039}}$	10,394.72	−0.03
I_3	$\frac{\text{Passenger capacity} \times \text{service ceiling}}{\text{Empty weight}}$	$\frac{4.75 \times 10^{-3}(W)^{0.822} \times 5.697(W)^{0.133}}{0.84(W)^{0.968}}$	0.032	−0.01
I_4	$\frac{\text{Horsepower} \times \text{climb rate}}{\text{Passenger capacity} \times \text{cruise speed}}$	$\frac{0.06(W)^{1.039} \times 742.48(W)^{0.04}}{4.75 \times 10^{-3}(W)^{0.822} \times 10.6(W)^{0.293}}$	884.78	−0.03
I_5	$\frac{\text{Wing loading} \times \text{cruise range}}{\text{Passenger capacity} \times \text{cruise speed}}$	$\frac{0.128(W)^{0.542} \times 3.86(W)^{0.564}}{4.75 \times 10^{-3}(W)^{0.822} \times 10.6(W)^{0.293}}$	9.81	−0.009
I_6	$\frac{\text{Wing loading} \times \text{cruise speed}}{\text{Passenger capacity}}$	$\frac{0.128(W)^{0.542} \times 10.6(W)^{0.293}}{4.75 \times 10^{-3}(W)^{0.822}}$	285.6	0.013

Table 3
The process of learning by scaling in the evolution of tractor technology, 1920–1968 [a]

Case	Dependent variable (Y)	Independent variable (W)	Estimated relationship	R^2	s
1.	Average belt horsepower	Average ballasted weight (lb)	$\log Y = -1.685 + 0.844 \log W$ (0.09)	0.68	0.06
2.	Average drawbar horsepower	Average ballasted weight (lb)	$\log Y = -2.637 + 1.039 \log W$ (0.14)	0.57	0.09
3.	Average fuel consumption (gal/h)	Average ballasted weight (lb)	$\log Y = -2.038 + 0.653 \log W$ (0.112)	0.44	0.07
4.	Average drawbar pull (lb)	Average ballasted weight (lb)	$\log Y = -0.36 + 0.978 \log W$ (0.07)	0.81	0.04
5.	Average number of cylinders	Average ballasted weight (lb)	$\log Y = -0.727 + 0.339 \log W$ (0.08)	0.28	0.05
6.	Average speed (miles per hour)	Average ballasted weight (lb)	$\log Y = -0.014 + 0.147 \log W$ (0.147)	0.02	0.09
7.	Crankshaft speed (r.p.m.)	Average ballasted weight (lb)	$\log Y = 1.787 + 0.349 \log W$ (0.21)	0.06	0.13
8.	Slip of drivers (%)	Average ballasted weight (lb)	$\log Y = 3.107 - 0.625 \log W$ (0.22)	0.15	0.14
9.	Average bore (in)	Average stroke (in)	$\log Y = 0.10 + 0.74 \log W$ (0.04)	0.89	0.02

[a] *Definitions:* R^2 is the coefficient of determination and S is the standard error of the estimate. Standard errors of the coefficients are indicated in parentheses.
Source of data: Sahal [17].

factors provided in table 2 can be interpreted in a similar way.

The second case examined here is the evolution of farm tractor technology during the time period 1920–1968. As before, several measures of technical progress are considered, including, changes in both performance variables (e.g. drawbar horsepower, fuel consumption and field speed) as well as design variables (e.g. average number of cylinders and bore dimension). The scale of technology is measured in terms of ballasted tractor weight in pounds. The parametric estimates of the relationship between chosen measures of technology and its scale are presented here in table 3. The explanatory power of these relationships is fairly good in most instances as indicated by the coefficients of determination. Thus, it is evident that there exist certain systematic patterns of technical progress. The results further indicate that the evolution of tractor technology is accompanied by a process of differential growth in its various dimensions. We find therefore that the increase in the bore has been proportionately smaller in comparison with increase in the stroke length (eq. 9, table 3). In consequence, the complexity of the tractor engine measured in terms of the number of cylinders has increased at an even pace in relation to its linear dimensions (eq. 5, table 3). The conclusion to be drawn is that a wide variety of innovations in arm tractor technology have also resulted from the process of learning by scaling.

A number of dimensionless products and dimensional constants based on the variables under consideration are presented in table 4. An application of the data in table 3 verifies that they are largely independent of scale of technology. Thus they may be justifiably regarded as invariant factors in the innovation process. The following examples may help make this clear.

The first invariant factor (I_1) listed in table 4 is the product of fuel consumption and slip of drivers. For the 6460 lb kerosene-powered tractor, Case 15–27, introduced by the J.I. Case Thrashing Co. in 1920 we obtain a value of $I_1 = 35.4$; for the 18,900 lb diesel-powered tractor, Massey-Ferguson 1135, introduced in 1973 we obtain a value of 30.55, despite the weight ratio of nearly 3:1. Interestingly enough, the latter model was not included in our sample. Yet we are able to predict its characteristics fairly well.

As a second example, consider the invariant factor (I_2) listed in table 4 which is specified as (drawbar pull × speed)/(drawbar horsepower). For the Case 15–27 the value of $I_2 = 375.19$; for the Massey-Ferguson 1135, $I_2 = 374.80$. The relative constancy or limited variation of these invariant factors convincingly demonstrates the existence of innovation avenues in the course of technical progress.

The final case examined here is the evolution of electronic computer technology over the time period 1951–1980. The specific measure of technical progress chosen for the purpose of analysis is a composite index of operations performed per second that incorporates several elements of speed: the speed of executing a particular arithmetic op-

Table 4
invariant factors in the evolution of tractor technology

Invariant	Composition	Scaling laws	Resulting parameter	Residual scale exponent
I_1	Slip of drivers × fuel	$1279.38(W)^{-0.625} \times 9.33 \times 10^{-3}(W)^{0.653}$	11.94	0.03
I_2	$\frac{\text{Drawbar pull} \times \text{speed}}{\text{Drawbar horsepower}}$	$\frac{0.44(W)^{0.978} \times 0.97(W)^{0.147}}{2.31 \times 10^{-3}(W)^{1.039}}$	184.76	0.08
I_3	$\frac{\text{Drawbar pull}}{\text{Fuel consumption} \times \text{no. of cylinders}}$	$\frac{0.44(W)^{0.978}}{9.33 \times 10^{-3}(W)^{0.653} \times 0.19(W)^{0.339}}$	248.21	−0.014
I_4	$\frac{\text{Drawbar pull} \times \text{slip}}{\text{Crankshaft speed}}$	$\frac{0.44(W)^{0.978} \times 1279.38(W)^{-0.625}}{61.23(W)^{0.349}}$	9.19	0.004
I_5	$\frac{\text{Crankshaft speed} \times \text{no. of cylinders}}{\text{Fuel consumption}}$	$\frac{61.23(W)^{0.349} \times 0.19(W)^{0.339}}{9.33 \times 10^{-3}(W)^{0.653}}$	1246.91	0.03

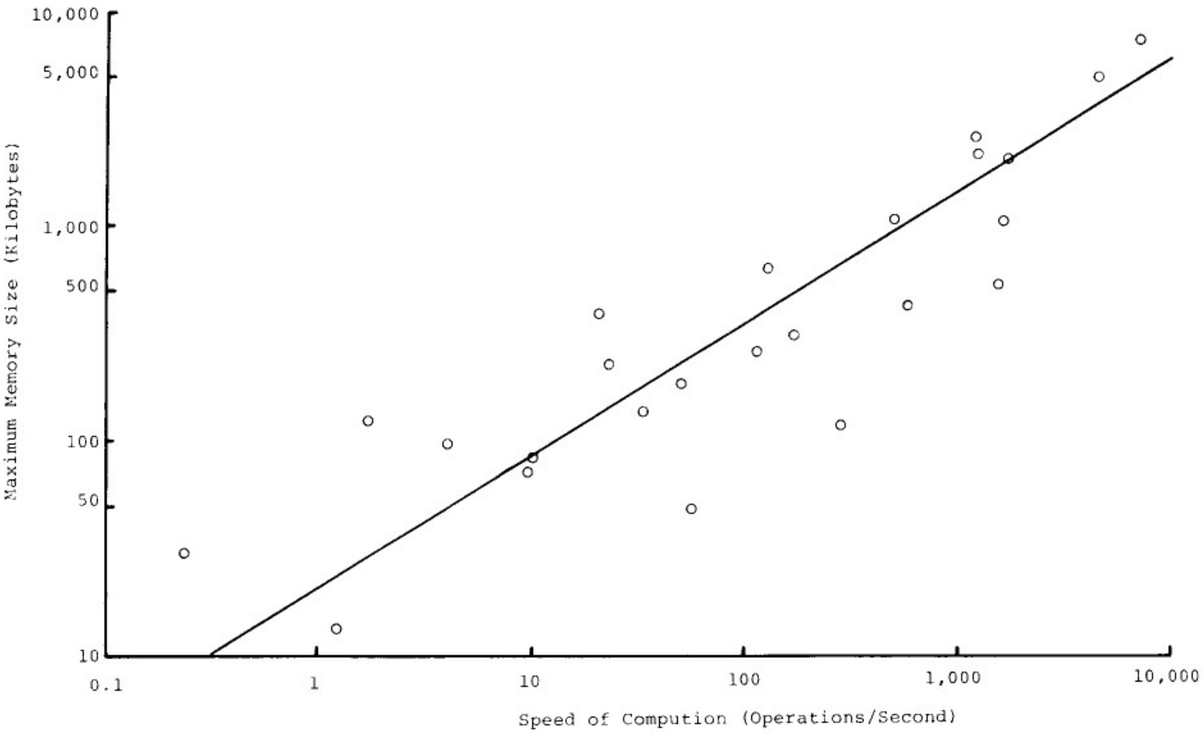

Fig. 11. Relationship between speed and capacity of digital computers, 1951–1980.

eration, the speed of solving a standard problem such as inversion of a matrix of any given size, the speed of reading the data into and out of memory, and speed of performing certain input/output functions. The scale of technology is measured in terms of maximum memory size in kilobytes.

The relationship between the chosen index of computational speed and capacity is depicted here in fig. 11. It can be seen that the agreement between the theory and the data is fairly good. Thus the proposed relationship explains more than 82 percent variance in the data. The slope of the speed capacity relationship is estimated to be 1.62. Finally, a close examination of the data reveals that the observed deviations from the estimated relationship are attributable to differences in the best practice and general practice technology.

5. The topography of technological evolution

In an important work in theoretical biology, C.H. Waddington has put forth the concept of "cherods" or necessary paths of development which bears several interesting parallels to the concept of "innovation avenues" presented in this study. Waddington was concerned with the study of embryonic development [23]. However, his terminology and pictorial representation of development is equally well suited to bringing out certain implications of the viewpoint proposed here. [7]

Our point of departure is a topographical representation of technological evolution depicted in fig. 12. A developing object such as an infant technology is shown here as a ball. Starting in a low basin, the ball may roll along any one of the two valleys. It is chance that determines the specific valley chosen. Once a specific valley has been opted for, the ball can keep rolling on its own momentum until the next branch point is encountered at which stage chance once again predominates over necessity. Such a representation of technological evolution is consistent with a point noted earlier: beyond a certain stage, quantitative changes in the scale of an object are invariably transformed into certain qualitative changes with profound implications for its morphological, func-

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[7] See also Prigogine for a somewhat similar view from a different premise [11].

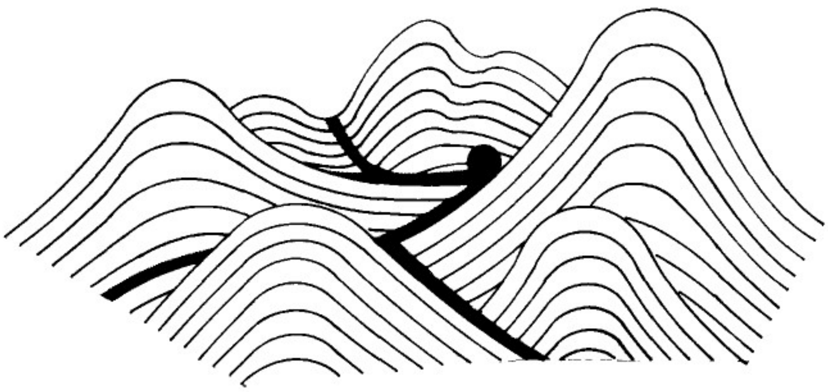

Fig. 12. The topography of technological evolution.

tional, and structural properties. Thus technical progress is neither wholly systematic nor wholly chaotic.

It should also be noted that the developing object can only ascend through various slopes if its form is progressively modified. Eventually, it may reach one of the several hilltops if its form is perfected through a process of constant refinement. The higher the peak, the greater the perfection. Relatedly, the lower the valley, the greater the difficulty of improvement and of leaving a given pathway. The overall topography itself can be altered by a wide variety of socio-economic forces. In consequence, the developing object may end up either remaining at a peak or climbing up successively higher peaks.

The proposed topographical representation of technological evolution helps clarify several points of interest. It is very generally the case that a technology, during the initial stages of its development, branches off in multiple directions. The development of the computer in the digital and analog form is an example of this, as is the development of the farm tractor along the track type and the wheel type. We find, moreover, that each of these multiple forms of technology evolves along a path of its own which in turn may split into separate paths from time to time. As an obvious example of this we find that the evolution of the digitial computer occurred along two paths: towards large computers and maxicomputers; and towards the minicomputer, microcomputer and the computer-on-a-chip in the offing. In essence, development of every technology is characterized by the existence of a unique evolutionary path or an innovation avenue. Occasionally, these avenues may also fuse together in what was earlier described as a process of integration symbiotic technologies.

Furthermore, the process of technological evolution is characterized not only by *specific innovation avenues* that concern individual industries as discussed above, but *generic innovation avenues* as well, that cut across several industries. As an example of the latter, the evolution of microelectronics is an important case in point. We find therefore that technology in both telecommunications and computer industries is evolving on a common generic innovation avenue.

Finally, it is apparent that the emergence of a new innovation avenue through *fusion* of two or more avenues or through *fission* of an existing avenue can give rise to sudden changes in the mode and tempo of technical progress. The conclusion to be drawn is that we should be prepared to expect surprises in the course of technological evolution because of – not in spite of – the existence of innovation avenues.

6. Conclusions and policy implications

This study has presented a general theoretical view of innovation processes. In its essence, one of the most important keys to understanding the origin of innovations is to be found in the simplest of facts: that the performance of every technology depends upon its size and structure. The proposed viewpoint markedly differs from the traditional, neoclassical economic theory viewpoint according to which the origin of innovation is to be found in the capital and labor intensity of the technology. Nevertheless, the two theoretical views are broadly complementary. Our view pertains to the *origin* of new techniques; the neoclassical view is relevant to the *resulting impact* on the activity of firms and industries concerned.

The proposed viewpoint also sheds new light on the controversy as to the relative importance of demand versus supply side factors in technical progress. According to the results of our investigation, the considerations of demand and supply are of little significance in and of themselves. Rather, their importance depends on their bearing on the internal structure of technology. it is the process of morphogenesis rather than demand or supply as such that is central to the process of innovation. What counts is not only the advances in scientific knowledge and the industry's sales *per se.* Above all, what matters is the fine structure of interaction between a multiplicity of factors including variables of both an economic as well as a physical nature.

In recent years, a certain ecological view of technology has gained increasing prominence among people from various fields and walks of life. The basic premise of "eco-philosophy" is to be greatly commended: the choice of a particular scale of technology has profound *socio-economic* repercussions. The viewpoint advanced here adds an altogether new and hithertofore overlooked rationale to this movement. It is that the size of technology has equally far-reaching implications for the possibilities of *innovation* as well. The proponents of eco-philosophy do of course have a valid claim, namely, that extreme in size is to be avoided for the sake of *humanity*. It needs to be added, however, that extreme in size is to be avoided for the sake of *creativity* as well.

The crux of the matter is that as technology is continuously made to become larger or smaller, the relationship between its size and structural requirements changes which, in turn, severely limits the scope of its further evolution. We find therefore that the origin of a wide variety of innovations lies in attempts to overcome certain natural limitations to a technology's betterment as a consequence of change in its scale.

These considerations in turn point to a trilogy of material, structural, and systems innovations corresponding to three main types of technological constraints. It is interesting to note that a number of input–output analyses indicate that innovations in the development of new materials have played a central role in the growth of industrial productivity [2]. According to the theory advanced here, this is to be expected.

The structural innovations concerning the nature of product design also play a vital role in technical progress, a role that is so obvious that it is often ignored. For example, consider the controversy surrounding the lack of technical progress in the automobile industry. Expert opinion would have us believe that the problem lies in certain institutional aspects of the industry such as its vertically integrated structure. Yet, such a viewpoint fails to explain why no such problem exists in the case of the telecommunications industry with a similar vertically integrated structure. If the considerations advanced here are any guide, it is conceivable that one root cause of the automobile industry's stagnation lies in the stagnation of its product design. This is evidenced by the industry's early decisions to discard certain potentially outstanding forms of design against the background of changes in consumer tastes – e.g. Ford's Model T car and Chrysler's airflow car – which may be likened to throwing away good money after bad. it goes without saying that the structure of an industry plays an important role in its innovative performance. it needs to be added however, that the structure of its technology may well be an equally important determinant of its performance.

Finally, the systems innovations that originate in an integration of two or more symbiotic technologies constitute the most important types of innovations. We have already discussed their significance at length. Suffice it here to add that their importance is likely to grow in the future. It has been observed that the thrust of national policy during the remainder of the twentieth century ought to be to promote the *diffusion* and transfer of certain key technologies such as microelectronics across broad areas of industrial application [15]. Equally important, it seems that the focus of the policy must shift once this objective has been achieved. Beginning from the twenty-first century, we may expect an accelerating trend towards what may be called the *fusion* of certain important technologies based on intermingling of knowledge from a wide variety of fields. In this respect, Kodak's new camera, an outcome of the joint effort of photochemists and electronics experts, seems a good pointer to the shape of things to come. Whatever the case may be, it seems imperative that management of R&D activity must show greater willingness and preparation to undertake essentially *trans-disciplinary* projects in the future.

The proposed trilogy of innovations is illustrative of another important point. It is that the constraining factors play an even more significant role in comparison with the facilitating factors in technological evolution. There is obviously a parallel here to a well known Biblical dictum: "Except a corn of wheat fall into the ground and die, it abideth alone; but if it die, it bringeth forth much fruit." This may be disconcerting to many policy planners. However, as the considerations advanced here make it plain, a major constraint is always a major catalyst to technical progress provided the management is willing to ensure adequate experimentalism in the conduct of R&D activity.

The results of our investigation further reveal that the process of innovation is best conceived in terms of a certain topography of technological evolution. Specifically, we find that in a wide variety of cases technical progress is characterized by innovation avenues that lay out various distinct paths of development. There are a number of important policy implications in this. To begin with, it is apparent in the light of our earlier research findings [13], that some innovation avenues are fairly broad whereas others are relatively narrow. Some may also be flat whereas others may be bumpy. Thus the direction and tempo of the innovation process may well be easier to adjust in some fields than in others. Accordingly, the appropriate technology strategy must differ from one industry to another.

Second, public support of R&D activity ought to be based on careful consideration of the relevant innovation avenues. In particular, the timing of support is crucial. Very generally, the development of a technology is best promoted when the underlying innovation avenue is approaching either a point of branching off or merging into several distinct but related innovation avenues. In most other circumstances, efforts to change the course of technical progress from without may not only be ineffective but wasteful as well.

Third, the process of technological evolution is determined by the interplay of chance and necessity rather than one at the exclusion of the other. Chance determines which amongst many innovation avenues will be chosen in the course of development. Once the development is well along a certain innovation avenue, necessity prevails until another point connecting other innovation avenues is reached. This brings chance back to the fore and the process continues. The implication is that there can never be one single optimal approach to the management of technology. Rather, an appropriate policy must be based on a judicious mixture of gradualism in the face of necessity and experimentalism in the face of chance.

Last, but not least, while technological evolution follows a logic of its own, its topographical make up depends upon a host of socio-economic forces at work. The conclusion to be drawn is that technology has a dual character: it is both an object and an instrument of socioeconomic evolution. In this respect, the proposed theory is admirably expressed by the maxim that "a hen is merely an egg's way of making another hen."

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