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Are There Discontinuities in Economic Development?

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ARE THERE DISCONTINUITIES IN ECONOMIC DEVELOPMENT?

This essay discusses the existence of discontinuities in knowledge and artefacts and their possible impact on economic development. Some new tools are presented which can help us to detect discontinuities and measure some of their properties, thus reducing the extent of subjectivity in the discussion. The essay concludes that discontinuities have an important impact on economic development by affecting the strategies, competencies and alliances that firms use.

Introduction

The concept of discontinuity is closely related to those of revolution and of qualitative change. The concept of revolution is closely associated with the political sphere, one of the most important recent examples being the Russian revolution in which imperial Russia was replaced by the Soviet Union. However, the same concept was also used outside the political sphere, for example by calling industrial revolution the process whereby a mode of production based on large factories, large machines owned by capitalists and employing salaried workers emerged out of a different economic system. Whatever revolution one considers, the states of the corresponding system before and after it are not comparable or qualitatively different. That changes in different systems can be both qualitative and quantitative had been understood at least since the time of Greek philosophers. One could say that a discontinuity is both a revolution and a qualitative change. However, the revolutionary, or discontinuous, nature of some changes, while evident for some scholars, has been disputed by others. Of course, from the opposite point of view the same changes that some called revolutions were interpreted as arising from the gradual accumulation of continuous changes. A good example of this is the Darwinian interpretation of the origin of species, stressing that completely different species had been generated by the gradual accumulation of small incremental changes. The presence and extent of discontinuity in these changes seems to depend on an individual interpretation and thus to have a subjective character. Furthermore, what seemed at a time qualitatively different entities sometimes turn out to be different assemblages of the same elements. For example, although chemical elements were once considered qualitatively different and not transformable into one another, since the beginning of the twentieth century it has been known that they are constituted by the same basic units. Thus, whether two entities are qualitatively different may depend on the power of human observation and understanding or on how finely long processes of transformation can be studied. This essay analyzes the presence and consequences of discontinuities in economic development. Such discontinuities are analyzed here at the two different though interconnected levels of artefacts and of knowledge.

Discontinuities, Artefacts and Knowledge

Artefacts have substantially empowered human beings with respect to other species throughout history, but the number of new artefacts has considerably increased since the industrial revolution. At least since the second half of the nineteenth century the creation of new artefacts has become increasingly science based. It is only since the second half of the nineteenth century that a growing proportion of the knowledge used in the creation of new artefacts started to be based on science. However, even today non-scientific knowledge continues to be used alongside scientific knowledge. Irrespective of the type of knowledge used in their creation and utilization, all artefacts are an interface between human knowledge of the laws of nature and human needs and wants. Any artefact satisfies a human need: mobility (cars, airplanes, etc), energy generation (water and windmills, etc). To satisfy these needs human beings have to understand some properties of the physical environment which allow them to create a useful artefact. Any artefact can be represented by two dimensions: its *internal structure*, a result of the understanding of the properties of the physical environment by the inventor, and the *services* it supplies to its users, intended to satisfy one or more human needs and wants.

These two dimensions of artefacts can be used both to detect examples of qualitative change and to examine some of its consequences. Some artefacts, such as cars, computers and airplanes, which have qualitatively different internal structures, can sometimes supply similar services. For example, cars and airplanes supply transport services. Thus, we can expect that the presence and extent of qualitative change will be greater for internal structures than for the services supplied.

Innovation is recognized today as one of the most important forces leading to economic and human development. All artefacts have been created and subsequently modified by innovations. Some of the concepts created to study innovation are closely related to discontinuities and qualitative change. Concepts such as scientific and technological paradigms, technological regimes and dominant designs indicate the presence of discontinuities between different artefacts, the knowledge used to create them and the organizations in which they are produced and used. Kuhn's (1962) concept of scientific paradigm indicates scientific theories based on qualitatively different and non-compatible world views. Technological paradigms, technological regimes and dominant designs, while sometimes referring to discontinuities which involve more limited cultural changes, indicate qualitatively different technologies.

One of the most important distinctions in the economics of innovation is that between radical and incremental innovations. Radical innovations are qualitatively different from any existing ones, while incremental innovations are improvements in what is recognizably the same technology. A technology is the set of knowledge and practices required to produce a given type of artefact. The time path followed by incremental innovations within a given technology gives rise to a *technological trajectory*. Such trajectories are trends followed during long periods of time by all the producers within a given technology and the corresponding industries. Thus, the discontinuity constituted by a radical innovation gives rise to a new technological paradigm and opens up a new market. Such a market subsequently grows due to the increasing productive capacity resulting from investment and to the rising productive efficiency and performance of the same technology. From the form in which it is initially created at the emergence of a new paradigm, a technology evolves by (a) becoming more efficient, thus producing its output at lower costs and prices, and by (b) improving the quality and differentiation of its products. The combination of (a) and (b) can considerably enlarge the market by including consumers who were too poor or who were interested in services not initially available. A clear example of this type of evolution is given by the technology of computers. Thus, in general, a technological paradigm seems to follow a life cycle, beginning with the discontinuity giving rise to a new paradigm and continuing with the stream of efficiency and quality enhancing incremental innovations. Finally, what was initially an innovative industrial sector matures and become part of the routines of the economic system, a set of routines that Schumpeter called the 'circular flow.'

In view of the previous discussion, and bearing in mind the gradual and discontinuous interpretations of technological evolution, we can formulate the following questions:

1) Could the type of economic development we have observed since the industrial revolution have occurred without discontinuities or, equivalently, simply by the accumulation of streams of incremental innovations?

2) Do the discontinuities which can be observed at the level of artefacts require corresponding discontinuities in knowledge?

Underlying these two questions there is a third one related to whether the gradualist and discontinuous interpretations are irreconcilably different or complementary interpretations of economic evolution. The previous discussion stressed the different role played by radical innovations which start a new technological paradigm and by the subsequent stream of incremental innovations which improve and expand the new market thus created. In this view, discontinuities and the gradual accumulation of incremental innovations are complementary. However, it can still be maintained that without the discontinuity constituted by the radical innovation starting the new technological paradigm, the subsequent stream of incremental innovations would not be possible unless the accumulation of incremental innovations could give rise to qualitatively different entities. Even if some room for debate is likely to persist, such controversy would lose part of its subjective character if we could develop some tools which allowed us to perform some form of empirical test, however partial, of the gradualist and discontinuous interpretations of economic evolution. Such tools would not only be useful conceptually but could also help firms and other organizations using technologies subject to discontinuities. Before examining the possibility of constructing such tools we need to answer the question regarding the relationship between artefacts and knowledge.

Knowledge

In the past, technology was described as the industrial arts and perceived as completely separate from science. Today, science is considered an important source of new technologies, although not the only one. However, can we say that science is the only source of knowledge for technology? Modern historians of science and technology tend to believe that science is a very important source of new technologies but not the only possible one. To study the relationship between science and technology we need a definition of knowledge which is sufficiently broad to encompass both science and other types of knowledge. A good starting point is to consider knowledge a structure intended to provide generalizations about physical and social phenomena. Such generalizations are obtained by establishing connections, or relationships, between the observables and variables which can be defined within particular systems. According to this view, knowledge is a network which can be described as a set of *nodes*, representing observables or variables, and of *links*, representing their connections. The presence of discontinuities in knowledge could then be detected by the emergence of new observables and new variables, which would give rise to new nodes in the network, and of the emergence of new and unexpected links between observables and variables which were previously considered unrelated. The network of knowledge would evolve in the course of time when new observables and new variables are discovered and when new relationships between them are found.

Within the above knowledge network, which can in principle encompass the whole of human knowledge, smaller knowledge structures can be identified as the knowledge bases of organizations, regions or countries. Thus, for example, we can identify the knowledge base of a firm or of a research organization. It is then possible to identify discontinuities in such knowledge bases by measuring some of their properties. Relevant properties of knowledge bases are their *coherence*, their *similarity* or its converse *cognitive distance*, and their *variety*.

We expect these properties to change in particular ways when a discontinuity emerges and to follow a different path during a period of incremental innovations. For example, the similarity between the past and the present knowledge produced within an organization can be expected to fall suddenly, and the corresponding cognitive distance to rise suddenly, as a discontinuity emerges. Thus, a sudden rise in cognitive distance or a sudden fall in similarity would indicate the onset of a knowledge discontinuity. Leaving aside the details of how such measures can be implemented, they give us a tool to detect the presence of knowledge discontinuities. Needless to say, these measures are approximations and may not answer all our questions in this field, but they can provide meaningful answers for many of them.

Artefacts

Assuming that the above measures can allow us to detect discontinuities in knowledge, we need now to describe similar tools which can used to detect discontinuities for artefacts. A representation of artefacts which can be used for this purpose is based on:

(a) A decomposition of the artefact into smaller units, called characteristics.

(b) Distinguishing the two dimensions of (b1), the internal structure of the technology, and (b2), the services supplied to users. Each of the two dimensions can be broken down into smaller units, called characteristics, similar to the traits of a biological organism. They are called technical characteristics for the internal structure and service characteristics for services.

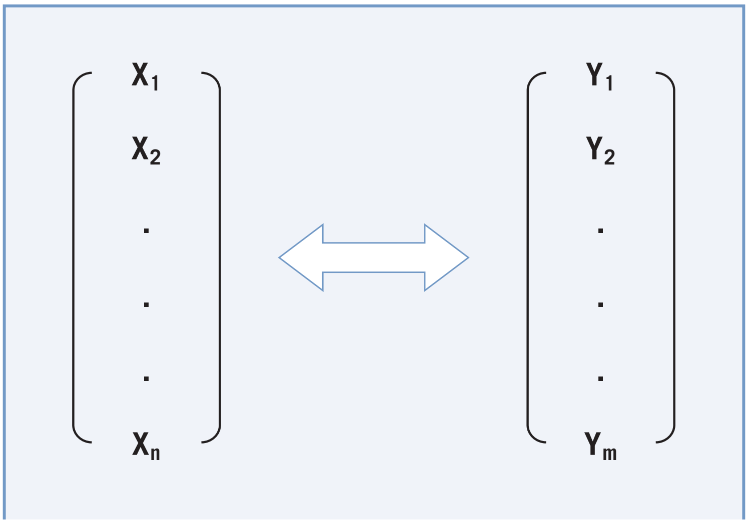

Figure 1: Twin characteristics representation of product technology. The X vector represents technical characteristics and the Y vector the services supplied.

Artefacts could differ for a part or for all of their characteristics. The dimension 'internal structure' contains characteristics relative to the technical nature of the artefact, while the services contain characteristics related to the human needs and wants that such services can be expected to satisfy (Figure 1).

This representation of artefacts is useful to detect discontinuities at two levels:

a) Different artefacts can be compared at a given time to see whether they are qualitatively different. Their qualitative differences can exist either in their internal structure or in their services or in both of them. Thus, two artefacts with completely different internal structures, such as electrical or internal combustion cars and digital and chemical cameras, can supply similar services (transport and visual reproduction).

b) The emergence of a new product can be considered a radical innovation when the new product has completely different (b1), internal structure, or (b2), internal structure and services, with respect to any pre-existing ones. In terms of Figure 1, (b1) would occur when the new product had completely different technical characteristics, while (b2) would occur when the new product had completely different technical and service characteristics with respect to any pre-existing ones. An example of (b1) would be given by cars as compared to horse-drawn coaches and of (b2) by computers when they were initially created.

This representation can be used to detect radical innovations capable of giving rise to new technological paradigms. A new technological paradigm will emerge when a new product is created which (i) has a new internal structure or (ii) has a new internal structure and supplies new services (Table 1).

Product Technologies	Type Of Transition	Technological Paradigm Shift
Cars	Internal structure	Internal combustion → electrical
Cameras	Internal structure	Chemical → digital
Watches	Internal structure	Mechanical → digital
Airplanes (creation)	Internal structure + services	Airplanes, emergence
Computers (creation)	Internal structure + services	Computers, emergence
Airplanes	Internal structure	Piston & propellers → jet

Table 1: Examples of different technological paradigm shift.

Table 1 gives different examples of technological paradigm shift. In all these cases the new and old product technologies do not share any technical characteristics, and in some cases any characteristics at all. However, if in addition to detecting the emergence of technological paradigms we want to be able to map the subsequent evolution of new product technologies, we expect to find cases in which all or part of the characteristics will differ not for their presence but for their quantitative levels. This is to be expected since most or all of the innovations following the emergence of a new technological paradigm tend to be incremental. In these cases we can develop measures of similarity and of distance based on product characteristics and similar to those described before for knowledge. We can expect the extent of similarity of two products to be higher, or their distances to be lower, the greater the number of characteristics they share and the more similar their quantitative levels are.

Example: Airplane Technology

By following the evolution of the characteristics of the products which have been created by the emergence of a technological paradigm we can detect the presence of particular trends, or trajectories, occurring within the paradigm. Thus, for example we can see that airplanes have become bigger and faster during their evolution. In fact, airplane technology has specialized in at least two trajectories, corresponding to large and (relatively) slow and to small and (relatively) fast planes. Such trajectories can be represented bi-dimensionally by means of a technique called principal component analysis (PCA) (Figure 2). In Figure 2 the large and (relatively) slow trajectory is almost parallel to the vertical axis and has been followed mostly by passenger transport planes. The small and (relatively) fast trajectory, which has been followed mostly by military planes, is almost parallel to the horizontal axis. The combination of the two trajectories shows that the evolution of airplane technology has been marked by a process of progressive specialization and differentiation.

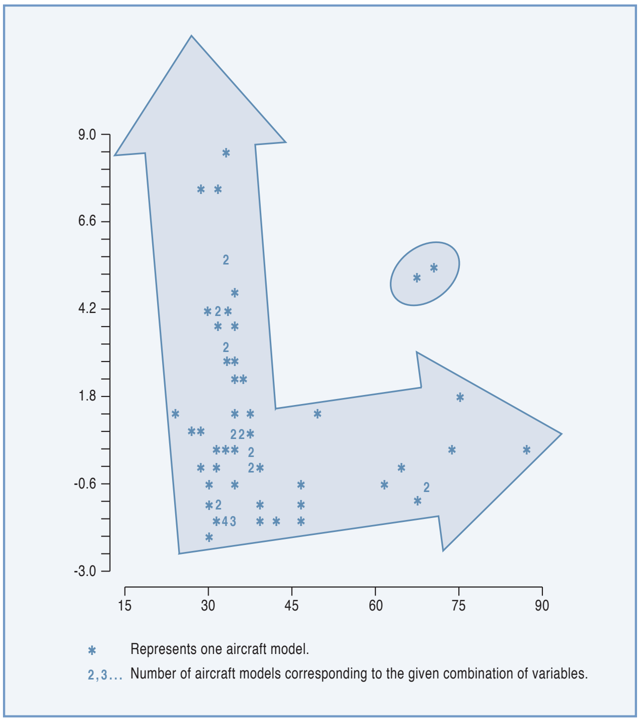

Figure 2: Trajectories followed by airplane technology during the period 1915–1990.

The reader of this essay might wonder what is the use of the above concepts. It may seem as if they can only be useful to economic or technological historians. Would the awareness of the existence of technological paradigms and trajectories be of any use to industrial planners and strategists? One might be tempted to conclude that these concepts are good descriptive devices but that they have no serious economic implications. The answer to these questions will become progressively clear during the rest of this essay. To start with we can notice that the two trajectories represented in Figure 2 were started by the new paradigm which established airplane technology but did not occur wholly within one paradigm. Starting from the 1930s a paradigm shift occurred in a subset of airplane technology, that of engines. The piston and propeller technology was gradually replaced by the jet engine technology. Such a paradigm shift was not wholly unexpected. We can see from Figure 3 that the speed achieved by the airplanes of the time increased after the beginning of the technology until the mid 1930s, then remained constant for some years and then started increasing again. With one exception the increase in the maximum speed started to slow down in the 1950s. We can then see that the rise in the maximum speed of the 1930s coincided with the paradigm shift from piston engine and propellers to the jet engine. Such a paradigm shift did not occur by chance but was induced by the diminishing returns encountered in the exploitation of the piston engine and propellers paradigm. The attempts to increase speed by installing more powerful engines and by turning propellers faster led to more turbulence without increasing speed. No such limit was encountered by the jet engine which did not need any propellers. The timing of the paradigm shift is likely to have been accelerated by the preparation for the second world war. The full development of the new engine technology occurred after the second world war and entailed a specialization of the new technology into three types: turbo propellers, turbo jet and turbo fan. The last of these technologies was developed to improve the fuel efficiency of large airplanes.

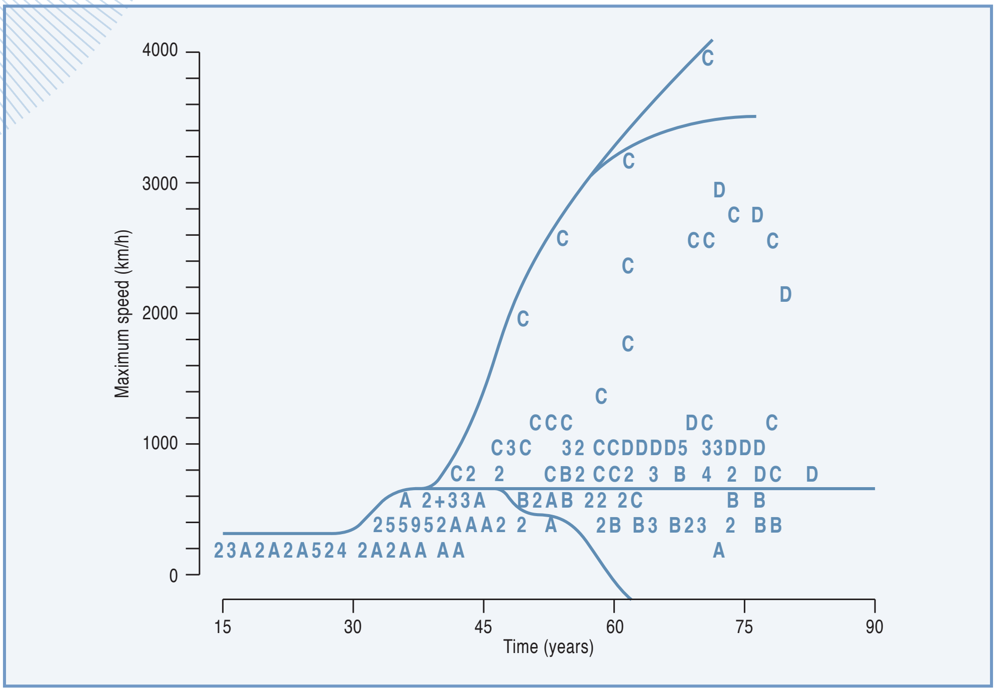

Figure 3: Technological trajectories and technological paradigm shift in airplane technology in the period 1915–1990. A: piston and propeller engines; B: turbo-propellers; C: jet engines; D: turbo fan engines.

In summary, we could say that technology was established by a new paradigm and that its subsequent evolution was shaped by the incremental innovations aimed at improving the performance of the original technology and by the paradigm shift in engine technology which occurred starting from the 1930s. This paradigm shift did not occur by chance but was induced by the diminishing returns encountered in the exploitation of the piston engine and propellers paradigm. This type of evolution closely parallels what Kuhn expected to occur in scientific paradigms, where theoretical anomalies encountered in the extension of an existing paradigm induced the emergence of a new one. The question which then arises is whether we can expect diminishing returns in all existing technological paradigms. No detailed empirical study has been done to enable us to answer this question. At this point we could say that manufacturing firms should be aware of the existence and dynamics of technological paradigms and be ready to adapt their strategies and competencies when required.

Example: Biotechnology and the Pharmaceutical Industry

Let us now go back to the analysis of discontinuities in knowledge. To do this the example of the pharmaceutical industry will be used. Until the 1970s pharmaceutical firms had relied on a knowledge base consisting mostly of organic chemistry to produce new drugs. In the 1970s this strategy started showing signs of diminishing returns. At the same time molecular biology, a new field of knowledge which began to develop in the 1930s, started showing the promise of industrial applications, the first of which was genetic engineering. Some pharmaceutical firms began to explore the possibility of replacing organic chemistry with third generation biotechnology, at that time consisting mostly of genetic engineering, to keep creating new drugs. At the present time most pharmaceutical firms have greatly changed their knowledge base by reducing the content of organic chemistry and by increasing that of biotechnology. This transition can be interpreted as a change of technological paradigm. We can now show the application of the measures of the knowledge base described above to interpret this paradigm shift.

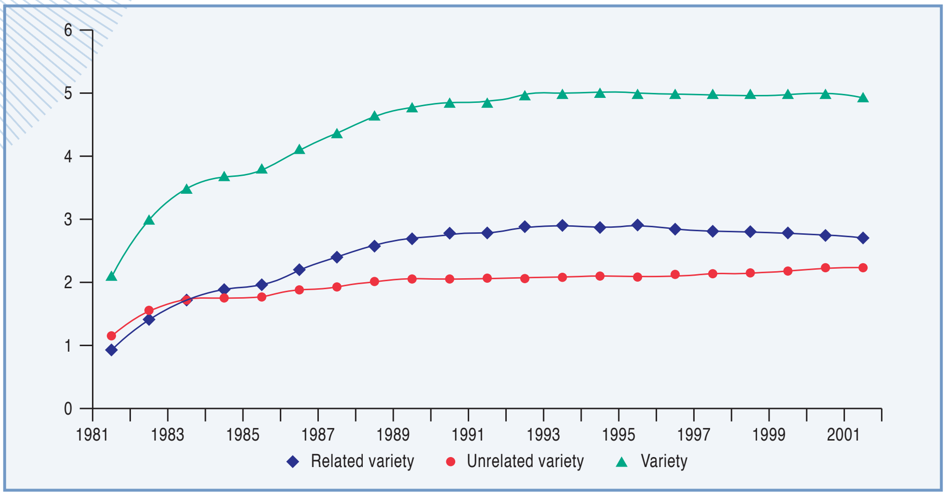

Figure 4: Variety of the knowledge base of biotechnology between 1981 and 2001.

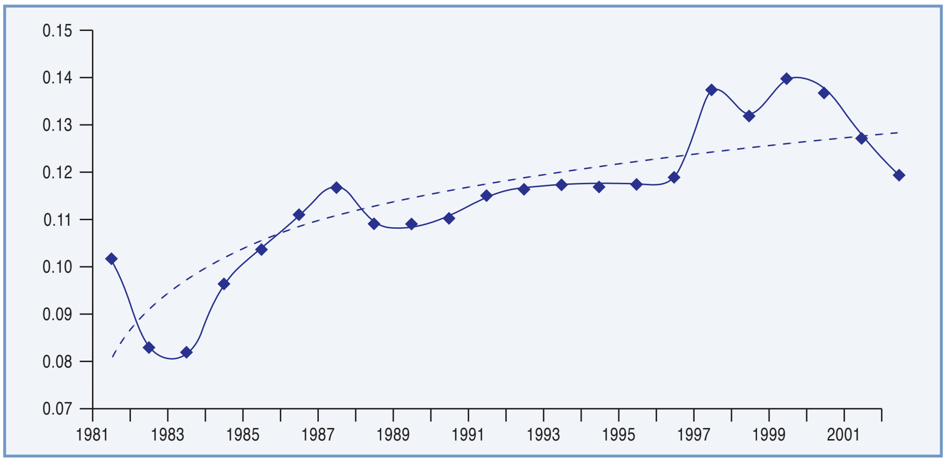

Figure 5: Coherence of the knowledge base of biotechnology between 1981 and 2001.

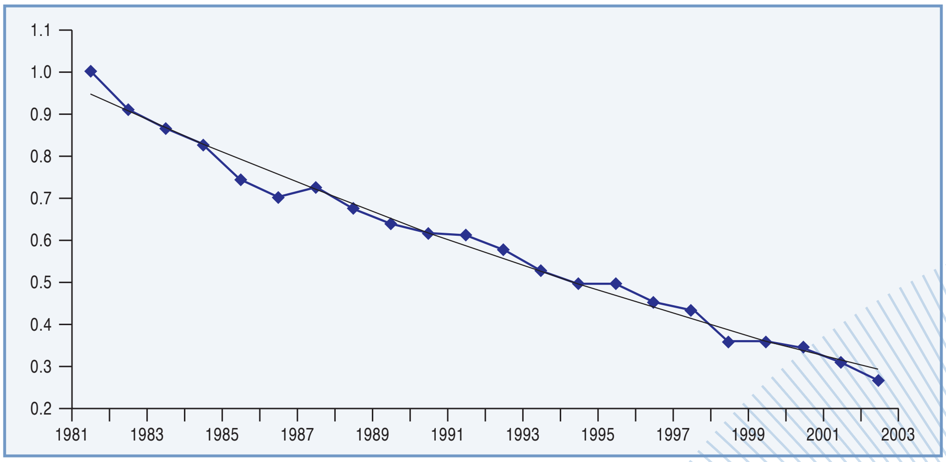

Figure 6: Cognitive distance of the knowledge base of biotechnology between 1981 and 2001.

In Figures 4–6 we can see the changes in three properties of the knowledge base of biotechnology, calculated from all the patents awarded by the European Patent Office between 1981 and 2001. Here variety measures the differentiation of the knowledge base, related variety towards closely related types of knowledge parts and unrelated variety towards unrelated and more radically different types of knowledge. Coherence measures the ability of firms to combine the different types of knowledge they need to use. Cognitive distance measures the dissimilarity of the present and of the past knowledge base of a firm or organization. After a new technological paradigm emerges we can expect the three properties of the knowledge base to be affected as follows:

- Variety to increase as the new paradigm is applied to more and more new types of industrial application.
- Coherence to fall initially as the new paradigm consists of knowledge which firms are not used to and then to recover as the firms learn how to combine new (to them) and old types of knowledge.
- Cognitive distance to rise initially and then to fall as the composition of the knowledge base changes from the old to the new types of knowledge.

The changes shown in Figures 4–6 correspond closely to the predicted ones and seem to confirm that starting from the 1970s in the pharmaceutical industry there was indeed a change of technological paradigm. It has to be immediately admitted that other cases in which one could suspect the existence of a technological paradigm shift do not conform closely to the pattern observed for the pharmaceutical industry. The concept of technological paradigm is very general and real cases are sometimes subject to more subtle influences. One of the strengths of the measures presented here is to enable us to detect these more subtle patterns and to map more precisely individual cases. For the purposes of this paper we can conclude that these measures of properties of the knowledge base allow us to detect discontinuities and to map their impact on particular industrial fields.

The example of biotechnology and the pharmaceutical industry is useful in understanding the relationship between knowledge and artefacts. Modern biotechnology emerged in the mid 1970s out of molecular biology, a new scientific discipline which had itself been created in the 1930s with the objective of applying to biology the methods of physics and chemistry. In this case a scientific paradigm, the emergence of molecular biology, preceded and led to a new technological paradigm, modern biotechnology, which provided the pharmaceutical industry with different routes to existing and new drugs. In the 1970s the knowledge that had become common for scientific organizations was still very novel and difficult to assimilate for pharmaceutical firms. However, this succession of events is not general and even today many new technologies are created without the need for previous scientific developments.

Implications of Discontinuities

We can now ask again the question with which the essay started: are there discontinuities in economic development? The answer based on the content of the essay is a cautious yes. Caution is required since what seems at first glance a discontinuity may turn out to be the result of the accumulation of many small incremental changes. The techniques and tools described in this essay help us better to articulate the question. A sudden rise in cognitive distance or a sudden fall in coherence indicate the onset of a knowledge discontinuity. Likewise, the emergence of a new product which has an internal structure qualitatively different from any pre-existing one indicates the onset of a discontinuity in artefacts. It has to be borne in mind that the techniques described above rely on data which are themselves obtained by implicitly assuming that certain entities are qualitatively different from others. For example, the measures of knowledge similarity or of cognitive distance are based on the International Patent Classification. If one were to reclassify patents and place in the same class those which were previously in two different classes, the values of these measures would change. Thus, the accuracy of these measures relies on the quality of the underlying classifications. If we assume that these classifications, while not perfect, are reasonable, we expect our measures to be a reasonable approximation and to enable us meaningfully to articulate the question which constitutes the title of this essay.

A different, though related, question is: irrespective of whether the phenomena described in this essay (e.g. paradigm changes in airplanes or in pharmaceutical industry) are discontinuities, do they have any implications for economic development?

The onset of a discontinuity forces incumbent firms to change their competencies and knowledge bases drastically. A change of this type requires a very long time and not all incumbent firms are likely to be successful in undertaking it.

Within the last 40 years the emergence of new knowledge fields with important industrial applications has led to great changes in industrial organization. High-tech start-ups and technological alliances have become standard components of many industries, but especially of those relying more closely on the progress of science. Within these industries high-tech start-ups played the role of 'translators' of the new knowledge that incumbent firms needed but with which they were largely unfamiliar.

During the last 30 years an important field of research in industrial economics has been that of the Industry Life Cycle (ILC). Many industrial sectors develop according to an ILC, the most notable feature of which is a very rapid growth in the number of firms, which reaches a maximum and then falls, giving rise in the end to an oligopoly. The ILC is started by a discontinuity, a radical and pervasive innovation, which creates a new market. The market can only be new if the new product technology is qualitatively different from any that is pre-existing. There are many more implications of the existence of discontinuities for economic development but the previous ones suffice to show that knowledge and artefact discontinuities are not just a philosophical preoccupation. Whether they are sudden bursts of creativity or whether they result from the accumulation of many small incremental changes, discontinuities are an important component of economic development.

Conclusions

This essay deals with the existence of discontinuities in economic development and concentrates on discontinuities in technological artefacts and in knowledge. As initially pointed out, although the existence of discontinuities has been largely discussed in epistemology and in the literature about innovation, there is no absolute consensus about the subject. The situation can be summarized as the existence of a debate between a 'gradualist' and a 'discontinuous' approach to economic development. The essay supports the existence of discontinuities by describing a number of concepts and tools which can be used to detect their presence and impact, thus rendering the debate less subjective. Finally, a number of important implications of the existence of discontinuities are discussed, including their impact on industry and firm organization and on the emergence of new markets. Such implications seem to require the existence of discontinuities, but the debate is unlikely to end here.

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Insights

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