Technological Inventions and Innovations: Cognitive and Social Factors as Evolutionary Forces

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Introduction

Technological traditions whose stability is ensured by both transmission and learning is, however, regularly the object of transformation thanks to invention/innovation. The latter are indeed major phenomena in the technological transformation processes. I propose here to analyze them by considering two levels of analysis: the individual and the collective ones. Invention, as a cognitive activity, occurs on an individual scale as opposed to innovation, which is the adoption of an invention on a collective scale, and therefore a historical phenomenon. In a first part, I deal with technological inventions, their order and mode of development, as well as the possible role of the individual in the differential occurrences of inventions. In a second part, I examine the mechanisms underlying innovation processes.

Technological evolution: gradual versus non gradual

I will consider first the hypotheses about the trend taken by technological evolution as evidenced by the evolution of the objects themselves, and second the hypotheses about the mode followed by this evolution, raising the debate between gradual versus non gradual technological evolution. The trend taken by technological evolution is assessed by examining the relationships between the techniques invented through the ages. It explains the “forms” taken by technological evolution. The mode followed by technological evolution is assessed by examining the passage from one technique to the other. Is this passage progressive, linear, by incremental additions or does it proceed by jumps? Accordingly, I will distinguish between continuous and discontinuous inventions. The hypothesis is that if both kinds of invention may participate to technological evolution, the mechanisms underlying their emergence and fixation may also vary.

Trend of technological evolution: cumulative character and order of development

Studies in the domain of the history of techniques show that techniques are cumulative in the sense that any transformation of a technique always incorporates previous knowledge (e.g. Creswell 1996; Gille 1978). In this regard, invention is often considered as incremental modification, or combination of pre-existing elements (e.g. Henrich 2010; Schiffer 2005).

Because techniques are cumulative, their evolution follows necessarily a certain order of development. As an example, the first ceramics are not made with the help of rotary kinetic energy, but with muscular energy only; pyrotechnologies do not begin with high temperature
technologies, but low temperatures, etc. In other words, inventions always take place within the logic suite of historically detectable antecedents. However, as specified by Creswell (1996: 21), the fact that techniques necessitate a certain order of development does not mean that this order is the same everywhere. Some groups can ignore certain stages and jump straight to more complex stages given environmental or cultural factors.

Now, this order of technological development, observed at a macro-scale and independently of the historical trajectories of the inventions, can be characterized in evolutionary terms. The hypothesis is that the general trend is towards less expense of human energy (Deforge 1989; Gille 1978; Simondon 1958). Such a trend would correspond to “laws of evolution” according to which techniques evolve logically from a state (called “abstract”) where the elementary operations underlying the manufacture of an object are first juxtaposed, to a state (called “concrete”) where these operations come into relation with each other and cannot be separated from each other, given their interaction in a synergistic fashion. The analysis is based on well documented lineages of numerous objects. Lineages gather objects that evolve from a stable technical principle. They have been constituted after an analysis of the genesis of the objects. In other words, they can be considered as a genealogy of physical principles (Creswell 1996:144). The corollary to the passage from the “abstract” to the “concrete” object is that, all other things being equal, objects will evolve towards lesser volume, lesser weight, lesser number of pieces, lesser response time, lesser price (Deforge 1989:281). As far as ceramic manufacturing techniques are concerned, in the southern Levant, one can trace an evolution of the coiling technique into the wheel coiling technique (use of the rotary kinetic energy for thinning and shaping coiled roughout) and, the latter, into the wheel throwing technique (use of the rotary kinetic energy on a clay mass). This latter technique which appears as an entirely mechanized manufacturing process can be considered as an ultimate stage in the development of ceramic techniques using the rotary kinetic energy in accordance with the “laws of evolution” proposed by Simondon. Indeed, the different operations are exerted in synergy through the use of rotary kinetic energy. Such a synergy is unique among the ceramic production techniques which are usually a series of “independent” operations like the wheel coiling technique. Hence, a considerable gain of time follows (Roux and Courty 1998).

Mode of evolution: gradual versus non gradual

Innovation appears in two ways: a) an autonomous and progressive development, not motivated by any specific social factors, responding mainly to technical rules; b) a
development by jumps between stages determined by social mutations. In the former case, the innovations can be considered as progressive, continuous. They develop by incremental additions in response to their own technical tendency up to a certain extent fixed by technical limits. In the latter case, the passage from one stage to another appears to follow a logarithmic function, and not a linear one. The innovations can be considered as discontinuous. They enable to go beyond the limits imposed by the internal logic of the techniques. They are not simply the combination or addition of pre-existing elements. They introduce new technological lineages. The technological jump produced by these techniques can be assessed quantitatively and qualitatively.

More precisely, discontinuous inventions are characterized by the introduction of new physical principles in the technological process (ex. new principles of propulsion), and, in this regard are limited in number, not corresponding to infinite re-combinations of pre-existing elements, but to new starting points in the evolution of technical objects reaching the end of their evolution. In other words, they punctuate technological history since each threshold or discontinuous inventions give rise to new lineages of objects characterized by new physical principles. These new lineages can coexist for a while with the ancestral lineages. It follows that the diagrams obtained when searching to represent, for example, the evolution of ceramic vessel lineages produced over the 5^{th}-1^{st} millennium in the Southern Levant are comparable to the ones of cladogenesis as shown in figure 1. In this figure, each new fashioning technique gives rise to a new lineage while the ancestral group resides alongside for a while. Each of them correspond to new physical principles: the wheel coiling technique is characterized by the use of the rotary kinetic energy (the new trait) for transforming clay walls made up of assembled elements (the ancestral trait); the wheel throwing technique is characterized by the use of the rotary kinetic energy (the ancestral trait) to transform a clay mass (the new trait) into a vessel. The passage to the wheel coiling technique is a first jump when assessed in terms of source of energy. The clay walls are now deformed under the combined energy of finger-palm pressures and rotary kinetic energy. The rotary kinetic energy requires the wheel to revolve around an axis with a sufficient kinetic energy to resist the strength of the pressures. It has to reach a speed of around 80 rounds per minute. The manufacturing time is divided by half. The jump is even bigger for the passage to the wheel throwing technique. The quantity of required kinetic energy for transforming a mass of clay into a vessel is much higher in order to resist the strength of the pressures on the clay mass. The wheel has to reach a speed of 150 rounds per minute. The manufacturing time is divided by 20.
When considering the lineage of the wheel coiled vessels in the Southern Levant, techno-stylistic variants are observed. Different fashioning methods are invented and new morphological types are wheel coiled in the course of the centuries. The different fashioning methods correspond to modifications of the stage at which the rotary kinetic energy is used (Roux and Courty 1998). In other words, they correspond to gradual variations following the same physical principle (use of the rotary kinetic energy on assembled elements). They can be plotted linearly when considering strength of pressures and manufacturing time. In this regard, there is no jump in between these methods. They represent continuous inventions led on the basis of the threshold introduced by the wheel coiling technique.

To sum up, empirical data suggest that technological evolution is made up of both continuous and discontinuous innovations, inventions by small-scale cumulative modifications not excluding radical jumps from times to times. The tempo of discontinuous innovations can be quite rapid. In the case of the wheel coiling technique in the Southern Levant, this new technical feature is clearly identified in strata of numerous sites dated from the second half of the 5th millennium BC whereas the use of the rotary kinetic energy for smoothing the surface of clay walls appears for the first time on a few vessels belonging to sites dated from the first half of the 5th millennium BC. On the contrary, the periods in between the discontinuous innovations appear to be long, considering of course the relative scale of historical time. Thus, the time period between the wheel coiling technique and the wheel throwing technique spans more than three millennia.

Cognitive activity and inventions

I will consider now the cognitive activity involved in discontinuous innovations in order to examine the possible role of the individual in technological evolution. The hypothesis is that the individual and its cognitive activity could act as a random factor in an evolution which otherwise follows, at a macro-scale, a necessary order of development.

Following the ecological approach and by reference to studies on the learning process of complex skills (Gibson 1979), invention can be considered as the result of an exploratory activity in the body-matter-energy system and the discovery, in the course of action, of the possibilities offered by the environment. Thus, the invention of the wheel-coiling technique has been interpreted as the result of a dynamic interaction between the task (discovery of the use of rotary kinetic energy for making bowls), the body (discovery of the skills for forming a bowl with rotary kinetic energy) and the instrument (discovery of the properties of the wheel for producing rotary kinetic energy) (Roux 2003).
As far as the discovery of the skills involved in discontinuous craft inventions, such as the ones involved in wheel fashioning, it can be viewed as a phenomenon in rupture with the tradition. Indeed, the difficulty in learning skills involved in any craft lies mainly in the mastery of the technique (physical modalities according to which raw material is processed) from which depends the mastery of the course of action (the sequence of sub-goals). The mastery of the technique itself lies in the control of the elementary movements which vary depending on the finished products. Once an expert, learning new elementary movements will imply a different tuning of the previously learnt elementary movements which will require again their rehearsal thousands of time. In this regard, emergence of new techniques - what characterize discontinuous inventions -, signal individuals who modified their elementary movements and developed new skills in rupture with what they learnt before. Thus, the wheel fashioning technique signals new skills different from the ones involved in the coiling technique; the wheel throwing technique signals new skills different from the ones involved in the wheel coiling technique (Roux 1989). Few years of apprenticeship separates these techniques.

Who were then these inventors able to break with the tradition and develop new skills? Let us recall that the learning process itself is carried out according to a model (the way of doing by a group for obtaining a given finished product) which is the transmitter’s. In this regard, there is never invention while learning motor skills. At the end of the apprenticeship process, the skills necessary for reproducing the tradition, and only these skills, are literally “embodied”. These skills then participate directly in the maintenance of the tradition, in the sense that it becomes difficult for the subject to conceive of making things in other ways, given the cognitive and motor skills they have developed which act as “fixers” of world views. However, field experimental studies have shown that subjects can develop different levels of expertise which are determinant in terms of cognitive behaviour. The expert is one who, when confronted with the constraints of the task is able to achieve the technological process through a constant dynamic fit between the state of the object and the next step. In other words, the expert has an extensive capacity to detect the appropriate information resulting from the ongoing course of action coupled with the ability to incorporate these into his action. Moreover expertise does not consist only in tuning as well as possible the properties of the system (the task-environment-organism system). The expert is also one who is able to force the system in one direction or another to adjust to new features (Bril et al. 2005). These new features can be “emergent performance problems”, new situations (e.g. new raw material) or “disturbances” in the system (e.g. flaws in the material).
By consequence, one would expect to find the invention process among individual-experts who are most familiar with the task’s constraints, i.e. experts who are able to explore body-material-energy properties, in this case going beyond the cultural representations which have formed their “way of seeing and doing”, solving problems and discovering new techniques and new skills (whether these problems appeared incidentally, by mistake, or were created voluntarily by the inventor). In the same way as engineers explore the laws governing the constraints concerned (material, energy) and test various solutions, inventors of discontinuous inventions are the ones able to go beyond their own cultural representations of technical tasks and the limits of the technical evolution of objects by discovering new physical principles and developing new skills. These individuals, like any expert in a given field, are exceptional as much for their skills as for their rarity as present day anthropological situations bear witness; in India, the inventions I saw were carried out by the most skilful craftsmen, attested as such by their production and reputation, one or two out of hundreds (inventions in pyrotechnology).

Hence the hypothesis that individuals and their cognitive activities might be a random factor in the evolution of techniques. This random factor could also well explain phenomena of technological convergences.

**The dynamic of technological discontinuous innovations**

The question raised now is how technological innovation occurs. How an invention made at an individual scale becomes an innovation at a collective scale? According to the dynamic approach, it is the temporal course of these two interacting variables, - the individual and the collective - that gives the technological system its faculty to adapt and bring about technological change (Roux 2003). More precisely, the phenomenon of innovation is considered as the result of a dynamic process emerging from complex interactions between the properties of its constitutive components - the technical task - here defined in terms of manufacturing process and skills, the environment, which serves as the source for materials used in the technical task, and the subject, who carries out the technical task and whose intention(s) are rooted in the group’s socio-cultural representations. The properties of these various components possess constraints (whether physico-chemical, biomechanical, environmental, or cultural). Innovations play on these constraints. They are initiated according to terms dependent on political, economic, social and/or religious situations in
which the demand for new objects, those made according to the new technique, plays a part. From this point of view, they invariably refer to particular historical scenarios.

These scenarios, even though particular, should enable us on the one hand to examine Creswell’s general hypothesis according to which jumps in technological evolution are determined by social mutations, and on the other hand to assess the relationships between the historical scenarios and their conditions of actualisation defined here as the context of craft production.

Discontinuous innovations and social factors

As an example of historical scenario, let us consider the emergence of the wheel-coiling technique. In the Southern Levant, the wheel-coiling appeared during the second half of the fifth millennium BC, during the period called “late Chalcolithic”, among farmer-pastoralist cultures whose material culture is especially remarkable for its innovations (in particular new ceramic and metallurgic techniques). Throughout this period lasting about 500 years wheel-coiling was only used for a single morpho-functional category – little open recipients with rectilinear walls called “V-shaped bowls”. These bowls are found as much on settlement sites as in sanctuaries or in a mortuary context where they are found systematically in primary and secondary tombs. A detailed study of the wheel-coiled bowls found on the site of Abu Hamid (Dollfus and Kafafi 1993), in the middle Jordan valley, suggests that these bowls had a ceremonial function. In dynamic terms, the innovation of wheel-coiling has been interpreted as having emerged from a complex interaction between an invention made on an individual scale, a favourable geological environment and a demand for objects of ceremonial value. Such a demand has been interpreted as emanating from an elite, given the function of the object and the politico-religious context. In other words, in the Southern Levant the innovation of wheel-coiling appears rooted in a demand initiated by an elite, at a period when new socio-political structures were emerging (Roux 2003).

This scenario finds numerous analogous in various chrono-cultural periods in the sense that the main technical inventions known from pre-industrial era apply to objects that are most often related to an elite context.

This suggests first that in traditional societies discontinuous innovations were initiated by individuals having some form of power - religious, political and/or financial-, second that these innovations were actualised, not for their techno-economic advantages, but for symbolic and/or social reasons. This argues in favour of Creswell’s hypothesis (1996) according to
which continuous transformations in techniques can be more or less autonomous, as part of an evolution, whereas discontinuous changes follow on from changes in society.

**Fixation and spread of discontinuous innovations**

It can take sometimes a few millennia before discontinuous innovations become predominant and therefore fixed. This is the case of the wheel fashioning technique in the Southern Levant (Roux 2008).

In the Southern Levant, the wheel fashioning technique was invented during the Chalcolithic period for the manufacture of ceremonial bowls. The Chalcolithic cultures collapsed in Early Bronze I (3800 BC). The ceramic material culture became characterised by strong regionalism and the appearance of new techno-stylistic traits (Miroschedji 1989). As for wheel-coiling, it practically disappeared from the Southern Levant, apart from a small geographic zone, and for a short period, Early Bronze IA. In Early Bronze IB, the rotary instrument is attested, but contrary to the previous periods the rotary kinetic energy was used for finishing operations only, not for thinning or shaping clay walls. Wheel-coiling is again present in Early Bronze II and III. The latter period, dated from the first half of the 3rd millennium BC, is characterised by a first wave of urbanisation marked in particular by the presence of fortified cities with monumental constructions. At Tel Yarmouth, a fortified town about 30 km South-west of Jerusalem and principal site of the Southern region of Southern Levant, two basalt tournettes have been found in the palace enclosure (Roux and Miroschedji 2009). Nevertheless, and contrary to every expectation, the vast majority of the ceramic objects were not made with rotary kinetic energy; only 3% were, suggesting that a very small number of craftsmen used the tournettes. This low number of craftsmen persisted steadily throughout the period of the Early Bronze III covering about 500 years. There was no borrowing of the wheel fashioning technique, which would have helped to raise the proportion of vessels formed on the wheel. In the Intermediate period (second half of the 3rd millennium BC) - a period of drastic historic changes marked by the collapse of cities – wheel fashioning disappeared again. It reappeared during the second millennium (Middle Bronze Age) when it became rapidly predominant.

It took thus three millennia for the wheel coiling technique to be widely adopted. It disappeared twice, once after the Chalcolithic period and one after the EBIII one. This developmental trajectory and its non linearity can be explained by examining the craft transmission context.
For the Chalcolithic period, a techno-petrographic study carried out on the scale of the Southern Levant showed that the craftsmen who formed the bowls on the wheel were small in number, itinerant and attached to an elite (Roux and Courty 2005). So wheel-coiling was handed down within a restricted circle of craftsmen whose status was distinct from the other more numerous potters who were installed at the various sites of the region and responsible for the utilitarian pottery. In Early Bronze III, wheel-coiling seems to have been the prerogative again of an elite, being exclusive to some specialised craftsmen who, given the presence of tournettes in the palace, must have had the status of craftsmen attached to the palace.

In summary, the craftsmen who used wheel-coiling in the 5th and 3rd millennium BC were a few specialist craftsmen attached to an elite, which reserved this technique for making objects for this elite. Most of production did not benefit from the innovation. This resulted in a technological system characterised as fragile, which explains why wheel-coiling disappeared twice and why it was so slow to develop. The fragility of a technological system can be defined according to the size of the network by which it is transmitted. If this size is too limited the system is fragile and cannot resist strong historic events, such as those which transform a society’s socio-economic structure. Thus - whether in the 5th or 3rd millennium - potters using wheel-coiling were few in number. Consequently, the transmission network was limited in size and confronted with the various historic upheavals which ended the Chalcolithic and Early Bronze Age cultures, the network was broken and the technique disappeared.

Fragile technological systems are in contrast to robust systems, which are characterised by transmission networks large enough for the technical feature to have enough redundancy to resist historic events. Thus, when wheel-coiling became prevalent in the second millennium BC and so transmitted by a large network, it resisted the various historic events which agitated the Southern Levant throughout history.

**Conclusion**

Technological evolution appears to be the result of both continuous and discontinuous innovations. Discontinuous innovations enable social groups to jump from one stage to another, to go beyond technological limits. They occur when there is a strong interdependency between techniques and societies. Organisation of societies is another important social factor which appears determinant in the emergence of innovation, notwithstanding the role of the individual which can act as a random factor for inventions to occur. Technical innovations,
such as the wheel forming techniques, met needs which at first were not economic, but social or symbolic. In the southern Levant, they developed slowly according to non linear trajectories.

**References**


CAPTION OF FIGURES

Figure 1. Diagram illustrating main divisions of ceramic fashioning techniques.