Via Po, 53 – 10124 Torino (Italy)
Tel. (+39) 011 6704917 - Fax (+39) 011 6703895
URL: http//www.de.unito.it

WORKING PAPER SERIES

**The economic complexity of technology and innovation.
A review article of *The nature of technology. What it is and how it evolves*,
by Arthur, W.B. Free Press, New York, pp.1-247.**

Cristiano Antonelli

Dipartimento di Economia "S. Cognetti de Martiis"

LEI & BRICK - Laboratorio di economia dell'innovazione "Franco Momigliano"
Bureau of Research in Innovation, Complexity and Knowledge, Collegio Carlo Alberto

Working paper No. 3/2010

Università di Torino

The economic complexity of technology and innovation. A review article of *The nature of technology. What it is and how it evolves*, by Arthur, W.B. Free Press, New York, pp.1-247.[1]

By Cristiano Antonelli, Dipartimento di Economia, Università di Torino and BRICK (Bureau of Research in Complexity, Knowledge and Innovation), Collegio Carlo Alberto, Moncalieri.

Technology is a problematic and intriguing area of investigation for economists ever since the discovery of the residual and the evidence about the limitations of textbook economics to explain economic growth. Economies of scale and increasing returns at large could not be accepted because of the devastating consequences in terms of the unlocking of the tight relationship between the theory of production and the theory of income distribution built at the core of basic model. This key relationship in fact holds only if and when the returns to scale are constant or diminishing, i.e. when the rate of increase of outputs is proportionate or less than proportionate to the rate of increase of inputs. Hence economists have looked to 'technology' as a black box that, for its special features, could solve the problem to combine individual action based upon marginal decreasing returns with the evidence about an increase in output that could not be justified without disrupting the foundations of textbook economics (Rosenberg, 1976 and 1994).

The attribution to technology of special features has made the trick possible for quite a long time. Kenneth Arrow has paved the way with the

[1] I acknowledge the funding and the scientific support of the Collegio Carlo Alberto and of the research grants of the University of Torino for the academic year 2009-2010.

attribution to technology of three basic characteristics of non exhaustibility, cumulativity and non-appropriability. These features enable the working of the following skilled and quite sophisticated argument.

Technology is non exhaustible in that it defies the standard attribution of decay and obsolescence associated with the use of many, if not all, economic goods. As such successive generations of agents can sequentially take advantage of the previous vintages of technology, stemming from the efforts of agents in previous economic periods to generate new technology. Provided that each generation has an incentive to contribute the accumulation of technological knowledge, the cumulative effects of the stock of technology provide an excellent explanation for the residual and hence for total factor productivity growth. At each point in time, in fact, the production process can take advantage of a larger stock of technology made available by the previous generations. Hence technology has unique features that differ sharply from the notion of capital: cumulativity contrasts and actually overcomes the working of marginal returns that apply to other forms of capital. Total factor productivity growth is not the result of the flow of technology generated at each point in time, but the result of the stock of technology cumulated through vintages of economic action (Arrow, 1962a, 1962b, 1969).

In order for the model to work, however, a theory of incentives for the continual investment of resources into the generation of new technology must be articulated. Otherwise the model would miss to provide a reasonable account for the reason why at each point in time agents would choose to keep augmenting the stock with additional flows of technological knowledge. The non- appropriability of the benefits of the stock of technology provides the missing chain in the argument. At each point in time agents have an incentive to invest resources in the generation of new technologies that add to the cumulated stock, because the appropriability of the economic benefits stemming from the use of the knowledge stock is impossible or limited, at best. Hence the second argument: agents have an incentive to keep investing resources in the generation of new technologies because they can appropriate only a part of the benefits stemming from the flow of resources that are invested in the generation of new knowledge. In other words the stock of knowledge is a public good that enters the downstream production function of the new vintages of goods and hence can generate additional output only if additional flows of knowledge are being generated at each point in time. The assumption of an active complementarity between the flows of technology and the stock of technology is the final refinement of the model (David, 1993).

The arrovian trick based upon the cumulativity and non-appropriability of technology has qualified most if not all the standard models of economics of growth and technological change, ever since the AK models. Romer's endogenous growth theory in fact is fully consistent with this line of analysis and actually contributes it with much insight. Endogenous growth theory implements the analysis of the key combination of cumulability and non-approrpiability with the complementary argument that the cumulability of technology is synchronic rather than diachronic. Agents can take advantage of the flows of knowledge spilling from the technology in use by other agents: non appropriability is synchronic among agents instead of diachronic among generations (Romer, 1990, 1994; Aghion and Howitt, 1998).

This framework must be praised for its extraordinary ingenuity. To borrow from the language of complexity theory, it combines in fact an account about technology as an artifact, that is an analytical representation of the intrinsic characteristics of the nature of technology, and technology as an action (Lane et al., 2009). Agents invest their time and their resources in the generation of technology because of the special features of the technology as an artifact. Incentives and decision making at the individual level about the investment of resources in the generation of new flows of technology, the working of the market place, the distribution of income according to marginalistic rules and the outcome in terms of an output that increases at a more than proportionate rate become fully consistent because of the clever combination of the analysis of technology as an artifact and technology as an action.

The problem with the arrovian model is that it is not the result of the actual investigation into the properties and the characteristics of technology. It seems more an ad hoc construct tailored to cope with the intrinsic limitations of economics in dialing with economic growth and specifically with the role of technological change in economic change. The shaky foundations engender the major weakness of the model i.e its strong implications in terms of homogenous and steady rates of improvements of technology across agents, regions and countries, historic times. The accumulation of technology and hence its benefits in fact should keep working at a steady state and no clue is given about the causes for possible variance. The empirical evidence shows, on the opposite, that the rates of growth of total factor productivity are far from stability: a lot of micro and macro variance is at play (Kuznets, 1930).

The new book of Brain Arthur on the nature of technology builds upon the results of his analysis of the structure of inventions and provides one of the most systematic explorations of the actual nature of technology (Arthur, 2007). In so doing it questions the basic assumptions laid down by Kenneth Arrow and provide clear and articulated analysis of the rugged and dynamic characteristics of technology as a complex landscape. Brian Arthur has made a remarkable effort to provide a comprehensive, organic and coherent framework to understand the nature of technology, what it is and how it evolves. The book explores with competence and vision the intrinsic characteristics of technology as an artifact. This is its strength. It does not develop the analysis of technology as a specific kind of economic action. This limits its scope. The confusion between the two levels is one of the main weaknesses of this work (Dosi and Grazzi, 2010).

The systematic organization of the book is consistent with the analysis and the methodology: it builds up from scratch, in a cumulative and systematic approach that provides a systemic account of technology and technological change. Combinatorial evolution is the first element in the building: novel technologies arise by combination of existing technologies. This evolution is complex, as opposite to Darwinian: "Darwin's mechanism does not work" (p.18). The application of the Darwinian mechanism to explore the nature of technology and its evolution is mistaken: it is able to explain the selection of new technologies but it is not able to explain the origins of novelty and innovation.

The origins of novelty can be understood only when the complexity of technology is appreciated. Technology is twice complex. First it is the result of the recombination of existing technologies and hence it is a system itself, made up of a variety of parts and components each of which is a technology. Second it is articulated in domains or families of consistent technologies. Each technology cannot be understood in isolation: it belongs to a domain and it is the result of a systemic recombination. New technologies arise when three different mechanisms are at work. Technological change takes place when science is able to identify new phenomena, that is new properties of natural events that be exploited and harnessed. Scientific breakthroughs provide room for technological opportunities. The exploitation of the new phenomena takes place however only when specific needs are expressed by the economic and social system or when a second mechanism is at work. Technological change takes place also because of the efforts made by intentional agents to overcome bottlenecks and limitations that become evident in the efforts of practitioners to stretch the functionality of each technology by means of the manipulation of the constituent components and subsystems. A weak component is identified and the efforts are finalized to substitute it. Structural deepening takes place and the design of subsystems that constitute each technology and each domain becomes more and more complex as the interdependence among the parts increases. The second mechanism can reinforce the first or take place independently. Finally, cross-fertilization across technologies both within and among domains provides continual stimulus to the process. Technological change that takes place in one domain can feed additional technological change by means of its eventual recombination with other, seemingly unrelated, domains. The access and use of knowledge external to each individual technology and to each domain is a primary source of technological change.

These mechanisms are constantly at work and feed each other. Technological change in fact provides new instruments that enable science to identify new phenomena. This in turn stimulates the generation of new technological knowledge in specific domains. New technological knowledge enables to modify existing technologies and technological subsystems that in turn require additional efforts to produce the structural deepening that overcomes local problems and emerging inefficiencies or technological ‘reverse salients’. The process is characterized by strong recursivity and it is typically ‘history dependent’. At each point in time the map of the technological systems articulated in systems, subsystems and domains each with their own design in fact is shaped by the process that has led to it. At the same time the map shapes the eventual dynamics of the process. Different maps might have merged with different sequences and different timing of origination of each individual event. There is no reason to believe that we live in the best of the worlds: at each point in time the selection of the new technologies is in fact very much affected by chance, including the sequential timing of discovery of new phenomena and of introduction of new domains and subsystems. Such an ongoing process is originated in the economic system and affects the economic system.

As Arthur recalls the economic system does not adopt a new technology but rather encounters a new technology. The system dynamics of technological change is shaped by three the interplay of two layers: the interdependence among technologies and the recombinations that generate new technologies. In so doing Arthur has provided a new and original account of the characteristics of technology as an artifact and has contributed the analysis of the system dynamics of technological change stressing the role of the complexity, i.e. the dynamic interdependence among the parts that constitute the system.

The analysis of cumulativity is now enriched by much a more sophisticated understanding of the variety of diachronic and synchronic connections that take place in the emergence of a new technology. The systemic analysis of Brian Arthur and the application of the basic economics of complexity provide the foundations for the understanding of the static and dynamics features of the key notion of technological landscape. Technology can now be seen as a rugged, dynamic and complex landscape where hills, mountains, valley and ravines contrast the beautiful planes implicitily assumed in the arrovian approach. This marks a major progress also with respect and implements the attempts to transplant the Kauffmann analysis of genetic landscape into technological landscapes (Kauffman, 1993; Kauffman, Lobo and Macready, 2000).

Brian Arthur however makes no explicit effort to develop the analysis of the implications of the nature of technology upon the foundations of the economic actions that are necessary to generate and use the technology. More specifically there is little clue to use the analysis of technology as an artifact to elaborate an economic theory of innovation and to assess the implications of the recombinant growth of technology for economic actions that are able to change technology and hence to account for total factor productivity growth. Total factor productivity growth is a key problem for economics as it consists in the generation of output for which there is not an obvious claimant.

If the generation of technology can be treated as a standard production process whereby efforts are stretched to the point where its marginal costs meets its marginal product there is no room for the generation of the residual. The characteristics of this specific production process and of the context into which they take place are indeed fascinating and worth much attention but their understanding does not contribute the grasping of the origin of novelty and unjustified -unjustifiable- increase in output levels beyond the increase in input levels.

Only when the analysis of the nature of technology meets the analysis of the economic actions that lead to the generation of a technology that produces more than expected the analytical loop can be closed and the arrovian model can be actually implemented and enriched.

The generation of technological knowledge and the introduction of technological change cannot be considered as the result of plain economic action conducted in equilibrium conditions. There is a major risk that the generation of technology is considered as the result of the intentional action of rational agents, guided by signals of scarcity (prices), incentives and opportunities (profits). Agents aware of the complex landscape into which the generation takes place may change their technologies, as much as their techniques. Once more there is the risk that the key role of the generation of technology into the generation of the residual is missed or attributed to the specific and given conditions of the landscape into which it takes place. Technology would risks again to be considered a special kind of a complicated mine where extraction is difficult and exposed to sudden and yet 'natural' stops and goes.

Quite on the opposite it is necessary to extract from the powerful analysis of the nature of technology provided by Brian Arthur a rationale for the action of economic agents without relying any longer on the simple combination of cumulativity and non-appropriability. The key question that remains under-investigated is: why do agents innovate and change their technologies and are able more output then expected? Here the analysis of Brian Arthur to provide an explanation based upon the key role of geographical clusters of innovators is quite disappointing as it is not able to elaborate a clear understanding of the rationale of economic agents of agents co-localized in the technological districts. Here the confusion between the levels of analysis is clear.

Taking advantage from the Schumpeter tradition of analysis of innovation, recently enriched by other contributions grown in the same Santa Fè cultural atmosphere, some steps forward can be made so as to articulate an economics of innovation as an action that complements the economics of technology as an artifact (Schumpeter, 1947a and b; Lane et alii, 2009).

The book of Brian Arthur is the result of an investigation about technology that misses a necessary and indispensable complement such as the investigation about technological innovation and its determinants.

The notion of innovation as a form of reaction introduced by Schumpeter (1947a and b) leads to articulate the hypothesis that myopic agents are induced to try and change their technology by specific conditions that affect their equilibrium conditions and push them to react by means of the introduction of innovations. The reaction can be adaptive or creative according to the conditions of the context into which it takes place. If the context provides the opportunity for the successful recombination of complementary bits of knowledge, the reaction will be successful and actually creative. Otherwise the passive adaptation to the new product and factor markets takes place. The search for new technology is local, as opposed to global and takes place locally in the close surrounding of their existing practices. The complexity of technology impedes all global vision and substantiates the localized character of the search. The local search takes place when firms are out of equilibrium and in so far it enables the introduction of a new technology is itself the cause of further and farther out-of-equilibrium conditions. The introduction of each new technology in fact affects the conditions in which each agent operates, perturbs product and factor markets, alters the technological landscape, defies all myopic expectations of equilibrium and in turn stimulates additional technological change (Antonelli, 2008).

The analysis of the nature of technology as a complex artifact adds key elements to understand that it is the result of a collective process, besides and beyond the intentionality of each agent. The understanding of the complexity of technology in fact enables to grasp the key role of the interaction and emerging complementarity among diverse agents, defined by the localized and hence idiosyncratic character of the technology under their specific command. Technological change and the introduction of innovations are the result of recombination of the localized technology broth about by each localized agent. Recombination works because technological knowledge is dispersed and fragmented into a variety of bits. Each agent has the control of a limited amount of technology. The complementarity and compatibility among each individual element is possible, but not given. Recombination is activated when economic agents stirred by sudden and un-expected out-of-equilibrium economic conditions try and search locally in order to generate new technology. In so doing they interact with other agents co-localized in both geographical and technological space. The progressive recombination of their bits of technology, by means of localized interaction, feeds the progressive and yet accidental emergence of nodes of complementarity of localized agents (Weitzman, 1994 and 1996; Patrucco, 2009).

The emergence of new technology is the result of a collective process of aggregation and integration of different bits of technology. Recombination contrasts fragmentation and takes place according to the distribution of agents in geographic and technological spaces plays a key role in the process as well as the organization of the system into which the interactions among agents take place. The notion of organized complexity defined by the structure and the quality of interactions is crucial to assess the actual chances that new technology actually emerges out of the confused and distributed process of local search into which a variety of agents participates with different endowments of competence and localized knowledge that are only potentially compatible and complementary. This approach enables to take advantage and appreciate the results of a long standing tradition of analysis in regional economics about the key role of localized interactions in determining the actual chances of introducing innovations (Malecki and Oinas, 1999; Frenken, 2006).

The integration of the notions of localized search stirred by out-of-equilibrium conditions and potential complementarity implemented by the organized complexity of networks of interactions is crucial to grasp the collective and systemic character of the emergence that feeds recombination and makes the generation of new technological knowledge eventually possible. The intentional action of agents in organizing the complexity of their environment plays a key role in the emergence of innovations as the collective outcome of communities of innovators.

Agents in fact can be credited with the capability both to innovate and to move in geographic, technological and organizational space by means of the creations of structures, such as networks and coalitions that support and qualify their interactions so as to increase their chances to perform effective recombinations (Lane et alii, 2009).

The analysis of technology and an artifact developed by Brian Arthur enables to enrich substantially the arrovian ingenuity and provides a context into which the analysis of technology as a specific form of economic action can make significant progress. Its integration with the analysis of the determinants of technological innovation at the agent level makes possible a major progress in our understanding of the economics of technological change and more generally in economics. The appreciation of technological innovation as an act moreover enables to fully grasp the basic engine of the self-sustaining dynamic interaction between technology and innovation. At each point in time innovation changes the technological landscape, but changes in the technological landscape change the conditions in which agents act and hence engenders new waves of innovations in a circular chain of causal relationship.

The integration of the analysis of technology as an artifact and technological innovation in fact enables to grasp the emergence of new technologies as the result of a system dynamics where the characteristics of the landscape and the dynamic rules of the process are at the same time the determinants and the consequences of the innovative action of myopic yet creative agents that try and react to the unexpected changes of product and factor markets by means of intentional efforts to change their technology. This approach enables to appreciate the limits of many typical assumptions elaborated in social sciences to cope with the analytical problems posed by technological change. Technological determinism fails to appreciate the role of the intentional action of agents that participate into the process and the consequent continual change in direction, intensity and effects of technological change. The traditional assumption of technological exogeneity upon which textbook economics elaborates is also clearly wrong, as technology is the product of economic action. For the same token evolutionary economics fails to appreciate the introduction of innovations as the result of an intentional process and risks to leave too much room to “darwinistic variations” that resemble too much the neoclassical manna.

This is definitely a book worth reading that hopefully will influence the debate with a significant discontinuity.

References

Aghion, P., Howitt, P. (1998), *Endogenous growth theory*, The MIT Press, Cambridge.

Antonelli, C. (2008), *Localized technological change. Towards the economics of complexity*, Routledge, London.

Arrow, K. J. (1962a), Economic welfare and the allocation of resources for invention, in Nelson, R. R. (ed.) *The rate and direction of inventive activity: Economic and social factors,* Princeton University Press for N.B.E.R., Princeton, pp. 609-625.

Arrow, K. J. (1962b), The economic implications of learning by doing, *Review of Economic Studies* 29, 155-173.

Arrow, K. J. (1969), Classificatory notes on the production and transmission of technical knowledge, *American Economic Review* 59, 29-35.

Arthur, B. W. (2007), The structure of invention, *Research Policy,* 36, 274–87.

David, P.A. (1993), Knowledge property and the system dynamics of technological change, *Proceedings of the World Bank Annual Conference on Development Economics,* The World Bank, Washington.

Dosi, G., Grazzi, M. (2010), On the nature of technologies: Knowledge, procedures, artifacts and production inputs, *Cambridge Journal of Economics* 34, 173-184.

Frenken, K., F. (2006), Technological innovation and complexity theory, *Economics of Innovation and New Technology* 15, 137-155.

Kauffman, S.A. (1993), *The origins of order. Self-organization and selection in evolution,* Oxford University Press, Oxford.

Kauffman, S.A., J. Lobo and W.G. Macready (2000), Optimal search on a technology landscape, *Journal of Economic Behavior and Organization*, 43, 141-166.

Kuznets S. (1930), *Secular movements in production and prices. Their nature and their bearing upon cyclical fluctuations*, Houghton Mifflin**,** Boston.

Lane, D.A. et alii (eds.) (2009), *Complexity perspectives in innovation and social change*, Springer, Berlin.

Malecki, E.J., Oinas, P. (eds.) (1999), *Making connections: Technological learning and regional economic change*, Aldershot, Ashgate.

Patrucco, P. (2009), Collective knowledge production costs and the dynamics of technological systems, *Economics of Innovation and New Technology* 18, 295-310.

Romer, P.M. (1990), Endogenous technological change, *Journal of Political Economy* 98, S71-102.

Romer, P.M. (1994), The origins of endogenous growth, *Journal of Economic Perspectives* 8, 3-22.

Rosenberg, N. (1976), *Perspectives on technology*, Cambridge University Press, Cambridge.

Rosenberg, N. (1994), *Exploring the black box*, Cambridge University Press, Cambridge.

Schumpeter, J. A. (1947a), Theoretical problems of economic growth, *Journal of Economic History* 7, 1-9.

Schumpeter, J. A. (1947b), The creative response in economic history, *Journal of Economic History* 7, 149-159.

Weitzman, M. L. (1996) Hybridizing growth theory, *American Economic Review* 86, 207-212.

Weitzman, M. L. (1998), Recombinant growth, *Quarterly Journal of Economics* 113, 331-360.