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Lab-oriented radical innovations as drivers of paradigm shifts in science

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LAB-ORIENTED RADICAL INNOVATIONS AS DRIVERS OF PARADIGM SHIFTS IN SCIENCE

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Abstract. An interesting problem in the economics of innovation and strategic management of labs is to explain the drivers of breakthroughs and paradigm shifts in science. This study confronts the issue by analysing a main case study: the technological determinant of the discovery of quasi-periodic materials that has generated a scientific paradigm shift in crystallography. Unlike user-friendly radical innovations, the study here detects some *specific radical innovations, defined lab-oriented and adopted by high-skilled users (i.e. researchers)* such as Transmission Electron Microscopy, which tend to support breakthroughs and scientific discoveries. This finding is the foundation for a framework, which endeavours to pinpoint the main characteristics and properties of these strategic lab-oriented radical innovations, which in turn spur scientific advances. Technological analysis of this study explains the critical role of specific technologies supporting knowledge creation and scientific discoveries to understand vital drivers of scientific fields and fruitful linkages that run from technological to scientific progress.

Keywords: Technological Innovation, Radical Innovation, Technological Paradigm, Technological Change, Paradigm Shift, Scientific Discovery, R&D Laboratory, Quasi-Periodic Crystals, Quasi-Periodic Materials, Crystallography.

JEL classification: O30; I31.

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* This research started in 2011 while I was visiting scholar at the Yale University and at the Georgia Institute of Technology. I am grateful to Dan Shechtman, winner of the 2011 Nobel Prize in Chemistry, for fruitful advices in occasion of the Distinguished Lecture "Quasi-Periodic Materials: Crystal Redefined" (in the Georgia Tech College of Management's LeCraw Auditorium on Thursday February 23, 2012). I also thank Trang Thai (School of Electrical Engineering at Georgia Tech) for constructive suggestions that substantially helped the development of this article. I thank The Engineering & Applied Science Library (Yale University) and S. Price Gilbert Library (Georgia Institute of Technology) for providing the scientific materials necessary to this research. I gratefully acknowledge the CNR - National Research Council of Italy - for financial support to develop this research project by vital visits at the Yale University in 2011, Georgia Institute of Technology (2011-2012), University of Strasbourg (BETA), UNU-MERIT, University of Toronto in 2013 and RAND (Washington D.C.) in 2014. I also thank Diego Margon for careful research assistance and Lili Wang (UNU-MERIT) for fruitful discussion of these scientific topics. The usual disclaimer applies.

1. Introduction and the problem

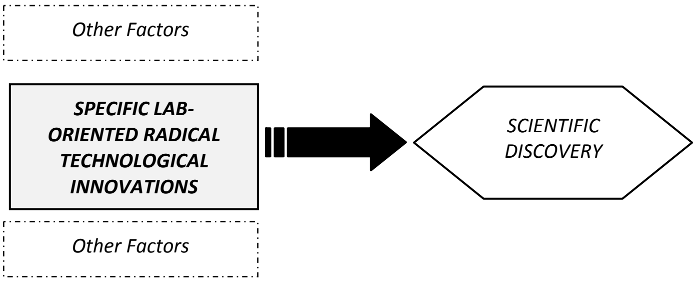
An interesting problem for the economics of innovation and strategic management is to explain *why* and *how* technological change spurs paradigm shifts in science to pinpoint the characteristics of specific technological innovations that support scientific discoveries. This study requires a "*dissection* (analysis)" of the pattern that runs from technological change to scientific discovery to *see* what elements and properties might play a critical role or at least influence the fruitful impact of specific technological innovations on scientific progress. Understanding *whether* or *not* this impact exists, and *how*, would help enhance our understanding of the fruitful interaction between diffusion of specific technological innovations and development of cutting-edge research fields in basic and applied sciences.

The economics of innovation and philosophy of science have provided many valuable insights about the origin of scientific paradigms (Laudan, 1977)[1]. At first glance, science and technology may be regarded as distinct social systems with different rules of conduct and largely autonomous in the influence that one has on the other (Price de Solla, 1965; Clark, 1987; Clarke, 1992; Kostoff, 1997). Bunch and Hellemans (2004, p. 436) state that: "It is often argued that science and technology develop independently and that new technologies only rarely are directly derived from scientific developments". However, the interaction between science and technology is high and critical scientific discoveries lay the foundations for paradigm shifts in science that afterwards support patterns of technological innovation and *vice versa* (Bunch and Hellemans, 2004 for some examples; *cf.* also Coccia 2005, 2005a; 2014, 2014a; 2014b).

This research intends to test the following hypothesis (HP) by a hypothetical-deductive approach *à la* Carl Hempel:

HP: Specific radical technological innovations “lab-oriented” can be a main determinant for scientific discoveries.

The *HP* can be schematically represented by the following linkage between key building blocks.



This study confronts the working hypothesis (HP) by analysing a vital case study in crystallography and by developing a framework, which endeavours to pinpoint the main characteristics and properties of technological innovations that support breakthroughs (*see* Corley and Gioia, 2011; Ireland, 2011)[2]. My research is based on the philosophical stance that there can be no adequate knowledge where causes are unknown (*cf.* Coccia, 2014). This study analyses the phenomena to be explained by scientific realism in order to achieve “at least approximate truths” (Thagard, 1988, p. 145; *cf.* Kukla, 1998). This approach can shed light on some likely linkages, mechanisms, characteristics and properties of the patterns of specific technological innovations that spur the development of fruitful scientific trajectories and as a consequence of vital scientific discoveries and paradigm shifts in science. Before discussing this main issue for economics of innovation and technology transfer, let me describe the background of this study.

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1 *Cf.* also Coccia, 2005; 2005a; 2009; 2010; 2010a; 2011; 2012; 2012a; 2014; 2014a, 2014b; Clark, 1987; Rothwell, 1994.

2. Theoretical background and related works

Economics of science and innovation have analysed the main characteristics of scientific revolutions through the scientific paradigm by Kuhn (1970; 1978; 1984), the research programs by Lakatos (1978) and so on (*cf.* Laudan, 1977; Barnes, 1982; Andersen, 1998; Büttner *et al.,* 2003). According to Kuhn (1970), scientific theories are based on a long-range development of "normal science" [3].Vital breakthroughs include not only radical changes of theory that have a significant impact on several research fields, but also changes of theory whose consequences are within a specific scientific discipline in which the change has taken place (Andersen, 1998, p. 3). The scientific revolution, therefore, can be *major* when there is a discontinuity with previous theoretical framework, and *minor* whether there is continuity between successive paradigms.

Scientific revolutions (major or minor) tend to support patterns of technological innovation in the long run. This technological change is based on different technological innovations and any change of a *specific* technological innovation by successive and improved generations that cope with greater efficacy *specific* technological, practical, and/or scientific problems. Technological innovations, as a consequence, can be of different intensity (*e.g.* radical, incremental, etc.)[4] and those of "very strong intensity" (Coccia, 2005a, p. 123), such as enabling technologies (Baker, 2012) can generate one and/or more technological paradigms[5]. The history of technology shows that there can be an interval between invention and innovations that in some cases can be more than 50 years (*cf.* Rosegger, 1980, p. 198ff). In

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[2] Other interesting papers for building theories are: Sutton and Staw, 1995; Di Maggio, 1995; Weick, 1989; 1995; Kilduff, 2006; Van de Ven, 1989; Whetten, 1989.

[3] " 'normal science' means research firmly based upon one or more past scientific achievements that some particular scientific community acknowledges for a time as supplying the foundation for its further practice'' (Kuhn, 1970, p. 10, original emphasis).

[4] *Cf.* Coccia (2005a), pp. 119-124.

[5] " 'model' and 'pattern' of solution of *selected* technological problems, based on *selected* principles derived from the natural science and on *selected* material technologies" (Dosi, 1982, p. 152, original emphasis).

general, technological paradigms are underpinned in advances of fundamental sciences, such as physics, chemistry and biology. This basic scientific knowledge has to transit in applied sciences (such as engineering)[6] in order to be embodied in radical technological innovations that can generate scientific, economic and social change.

In fact, Nelson (2008, p. 489) argues that:

> the research in the engineering disciplines and applications oriented sciences aims to develop understanding of what is going on in the operation of the relevant field of practice, so as to illuminate how to advance it.

Nelson (2008) also seeks to clarify why certain technological paradigms support fruitful scientific and technological progress in comparison to others. Some determinants are the economic and human resources (*e.g.* R&D intensity of countries, number of researchers in science and technology, etc.) based on research policy aimed at strategic technology programs, and to a lesser degree "'effective demand'" of markets (Nelson, 2008, p. 487; *cf.* Rosenberg, 1983)[7]. In addition, a main driver is also the "'interest and goals' of professional 'knowledge-seekers' " (Clark, 1987, p. 40, original emphasis).

As a matter of fact, the origin of a new scientific and technological paradigm can be due to some scientific and technological forces that "break-out" current trajectories (*cf.* Dolfsma and Leydesdorff, 2009).

Sahal (1985) argues that:

> 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 (p. 70). . . . 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 (p. 79, original emphasis)

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[6] Engineering can be considered an *intermediate scientific field* because links basic sciences (such as physics) to practical technological applications in order to solve problems of different fields (*cf.* Nelson, 2008, p. 491 and p. 494).

[7] Nelson (2008) claims that the evolutionary growth of technological paradigms can be also supported by a process of learning from experience based on the ability to identify, control and replicate practices, in other words: "for progress to be made the practices involved must have a certain amount of 'routines' about them"

Generally speaking, a technological innovation *A,* during its diffusion, has a multiplicity of social, economic and technological impacts. In particular, technological innovation *A* can affect simultaneously and/or not simultaneously:

a) Other technological innovations *A1* and *A2* (related to *A*) and/or technological innovations B, C, D, E, F … (not related to *A*): this generates the *technological impact of the innovation A on other technologies;*

b) Scientific patterns, generating vital breakthroughs and new scientific discoveries: *technological impact of A on scientific fields*;

c) People and society by new social habits and needs: *technological impact of A on society*;

d) Economic system and structural indicators (*e.g.* labour, capital, productivity, GDP growth, etc.): *technological impact of A on economic system*.

The purpose of this paper is to *see* whether the empirical evidence supports the hypothesis (HP) that paradigm shift in science can be explained by driving force of *specific* radical technological innovations, defined lab-oriented. In particular, the present study explains the technological impact of innovations on scientific research (as indicated in the bulleted point *b*), by analysing a main case study[8] in crystallography (*i.e.* the discovery of quasi-periodic materials). This research endeavours to explain, by a theoretical framework underpinned in a critical evidence, the characteristics and properties of some technological sources based on specific radical innovations, which tend to spur scientific discoveries.

(Nelson, 2008, p. 488, original emphasis; *cf.* also Nelson and Winter, 1982, *passim*). *Cf.* Coccia, 2009; 2010; 2011; 2012a; 2014; 2014a.

[8] For building theories from case study research, *see:* Eisenhardt (1989), Eisenhardt and Graebner (2007).

3. The discovery of Quasi-periodic crystals: a scientific paradigm shift in crystallography

Crystallography is the science of condensed matter that examines the atomic or molecular structure and its relation to physical and chemical properties. The year 2014 is also The International Year of Crystallography, a main event promoted by UNESCO and the International Union of Crystallography[9]. International Union of Crystallography (IUCr)[10], prior to 1992, stated that: “A crystal is a substance in which the constituent atoms, or ions are packed in a regularly ordered, repeating three-dimensional pattern” (*cf.* Kittel, 1986).

A characteristic of crystals is their regular shape by space-group symmetry (Harker and Harker, 1971)[11]. The crystals studied by von Laue[12] in 1912 were ordered and periodic until 1982. Among the rotational symmetries 2-,3-,4- and 6-fold axes are allowed, while 5-,7- and all higher rotations are disallowed.

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[9] UNESCO (2014) points out: “2014 marks the centennial of the birth of X-ray crystallography, thanks to the work of William Henry, William Lawrence Bragg . . . and Max von Laue. In fact, it was discovered that X-rays could be used to ‘see’ the structure of matter in a non-intrusive manner, thus beginning the dawn of modern crystallography —the science that examines the arrangement of atoms in solids. Although crystallography underpins all of the sciences today, it remains relatively unknown to the general public; crystallography has become the very core of structural science, revealing the structure of DNA, allowing us to understand and fabricate computer memories, showing us how proteins are created in cells and helping scientists to design powerful new materials and drugs . . . . It permeates our daily lives and forms the backbone of industries which are increasingly reliant on knowledge generation to develop new products, in widely diverse fields that include agro-food, aeronautics, automobiles, cosmetics and computers as well as the electro-mechanical, pharmaceutical and mining industries. The International Year of Crystallography 2014 highlights the continuing importance of crystallography and its role in addressing post-2015 development issues such as food security, safe drinking water, health care, sustainable energy and environmental remediation”.

[10] The IUCr is an International Scientific Union. Its objectives are to promote international cooperation in crystallography and to contribute to all aspects of crystallography, to promote international publication of crystallographic research, to facilitate standardisation of methods, units, nomenclatures and symbols, and to form a focus for the relations of crystallography to other sciences (IUCr, 2014).

[11] Scientists have to beam X-rays onto molecules, which scatter the rays, just as light is reflected when it hits any object. The shattered rays — called the diffraction — are then reassembled into an image by a computer program. But since the diffraction of a single molecule would be weak to the point of unintelligibility, scientists get the molecules they’re studying to clump together into crystal form. This highly ordered structure, made up of vast amounts of molecules, makes X-ray diffractions — the main tool of crystallography — easier to study.

[12] He won the Nobel Prize in Physics in 1914 for his discovery of the diffraction of X rays in crystals. His researches showed that crystals have a molecular structure that regularly repeats its arrangement. This study enabled to analyse the structure of crystals and engendered the solid-state physics, an important field in the development of modern electronics.

Lidin (2011) argues that:

> The proof is very simple, and it is instructive to consider how two parallel 4-fold or 6-fold axes of rotation generate translational symmetry, while two parallel 5-fold axes of rotation clearly cannot coexist. This proof makes it obvious that 5-fold symmetry is incompatible with translational symmetry, and hence with crystallinity.

Shechtman *et al.* (1984) obtain a diffraction pattern (shattered rays - called diffraction - are reassembled into an image by a computer program) from an alloy based on aluminium and manganese that exhibits perfect 5-fold symmetry with sharp Bragg peaks, in violation of previous theory, briefly described above. In particular, Shechtman and Blech (1985) show in detail the approach that an alloy has the point group symmetry of icosahedrons, a polyhedron with 20 faces that are all equilateral triangles, and that has six 5-fold axes (Fig. 1).

Levine and Steinhardt (1984) claim this scientific concept as “quasicrystallinity”, based on a new type of organisation in condensed matter. This breakthrough has enriched crystallography by both periodic crystals and aperiodic crystals with icosahedral, octagonal, decagonal and dodecagonal rotational symmetries (Kuo, 1994, p.1).

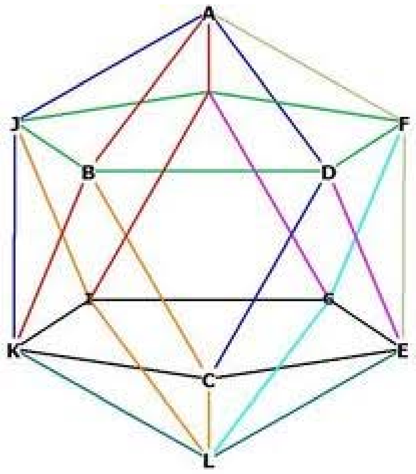

Figure 1: The Icosahedron: many of the quasi-periodic crystals have icosahedral symmetry

The main objection to quasi-periodic nature of quasicrystals (QCs) is by Pauling (1985; 1987) that tried to prove that QCs are really just twinned periodic crystals. Later, in 1987, an experiment based on X-ray diffraction pattern (X-ray transmission Laue photograph of i-ZnMgHo QC) convinced the community of crystallographers that 5-fold symmetry can exist in crystals. After that, scholars considered the old definition of crystal not sufficient to cover this new class of ordered solids, and as a consequence *The International Union of Crystallography* (1992) in the Report of the Executive Committee for 1991 provides a new definition of crystal:

> by crystal we mean any solid having an essentially discrete diffraction diagram, and by aperiodic crystal we mean any crystal in which three dimensional lattice periodicity can be considered to be absent.

The authoritative definition by International Union of Crystallography (1992) broadened the concept of crystals and lays the foundations for the widespread acceptance of the new scientific paradigm shift of Quasi-periodic crystals (QCs). The discovery by Shechtman *et al.* (1984) has opened the Era of Quasi-periodic crystals, generating a paradigm shift in crystallography that may be a considered a (*minor*) *scientific revolution*.

QCs are promising candidates for coatings, hydrogen storage materials, thermal barriers, infrared sensors, aluminium alloys, surgical tools and electric shaves. Jenks and Thiel (1998) suggest that quasicrystalline materials may be better catalysts than their crystalline counterparts. Scholars show thermodynamic and electronic properties of QCs and that the surfaces of Al-based behaves as if they are chemically similar to pure aluminium (*see also* Li and Liu, 2012; Liu *et al*., 2013; Sakly *et al*., 2014).

4. A driving force for breakthroughs: the vital role of the lab-oriented radical innovation - Transmission Electron Microscopy

Quasi-periodic crystals (QCs) are not rare because there are hundreds of them; QCs can be thermodynamically stable and made by many manufacturing technologies (casting, electro deposition, etc.)[13].

Hence,

Why QCs were never discovered before 1982?

What is one of the main driving force that has supported the discover of Quasi-periodic crystals?

A main determinant of the discovery of QCs can be considered the Transmission Electron Microscopy (TEM) and high-energy electron diffraction (Thiel, 2004), which are here defined as *lab-oriented radical technological innovations*.

These types of specific radical innovations are aimed at research laboratories[14] and adopted by high-skilled users, such as researchers in basic and applied sciences (*cf.* Almirall and Wareham, 2011; Ritala and Sainio, 2014; Mirabeau *et al.,* 2014). *Lab-oriented radical innovation* is a vital means to increase the performance and capabilities of the users in the discovery process[15], and in general in the scientific research.

In particular, TEM is a lab-oriented radical technological innovation where the electrons are accelerated by an electrostatic potential in order to gain the desired energy and determine the wavelength before they interact with the sample to be analysed. TEM operates by electrons

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[13] This part is a re-elaboration of the distinguished lecture by Shechtman (2012).

[14] See Crow and Bozeman (1998) for a comprehensive study of roles played by R&D laboratories in national innovation system.

[15] *Discovery process* is specific for industries. In general, discovery process is based on the following steps: *Research* (Target identification and validation; Assay development; Lead identification; Lead optimisation; Pre-development); Development; Commercialisation and Life cycle management (*Cf.* Coccia, 2014c).

that are accelerated at 100-1000 kV to a velocity approaching the speed of light; the associated wavelength is five orders of magnitude smaller than light wavelength and the resolution of the material imaging and structure determination is at atomic level (Hawkes, 2007; Fultz and Howe, 2007; Rose, 2008; Reimer and Kohl, 2008).

The origin of TEM is by Ernst Ruska in 1932 (Nobel Prize in Physics in 1986). The first TEM was capable of only 16 times magnification. Siemens in 1936 improves the TEM imaging properties and in 1939 the first commercial TEM is installed at the I. G Farben-Werke Department of Physics in Germany. The associated scanning transmission electron microscopy (STEM) is improved in 1960s-70s by Albert Crewe that develops the field emission gun at the University of Chicago (Crewe *et al.,* 1969); he adds a high quality objective lens to create a modern STEM. Crewe *et al.* (1970) also develop the cold field electron emission source and build a STEM able to visualise single heavy atoms on thin carbon substrates.

A conventional Transmission Electron Microscopy (TEM) is constituted by (*see* Figure 2):

- 2-3 condenser lenses to focus on beam on the sample;
- an objective lens to form the diffraction in the back focal plane and the image of the sample in the image plane;
- some intermediate lenses to magnify the image or diffraction pattern on the screen; if the sample is lesser than 20nm[16] and constituted of light chemical elements, the image presents a very low contrast when it is focused. To obtain an amplitude contrasted image, an objective diaphragm is inserted in the back focal plane to select the transmitted beam.

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[16] nm (*nanometre*) is a unit of length in the metric system, equal to one billionth of a metre.

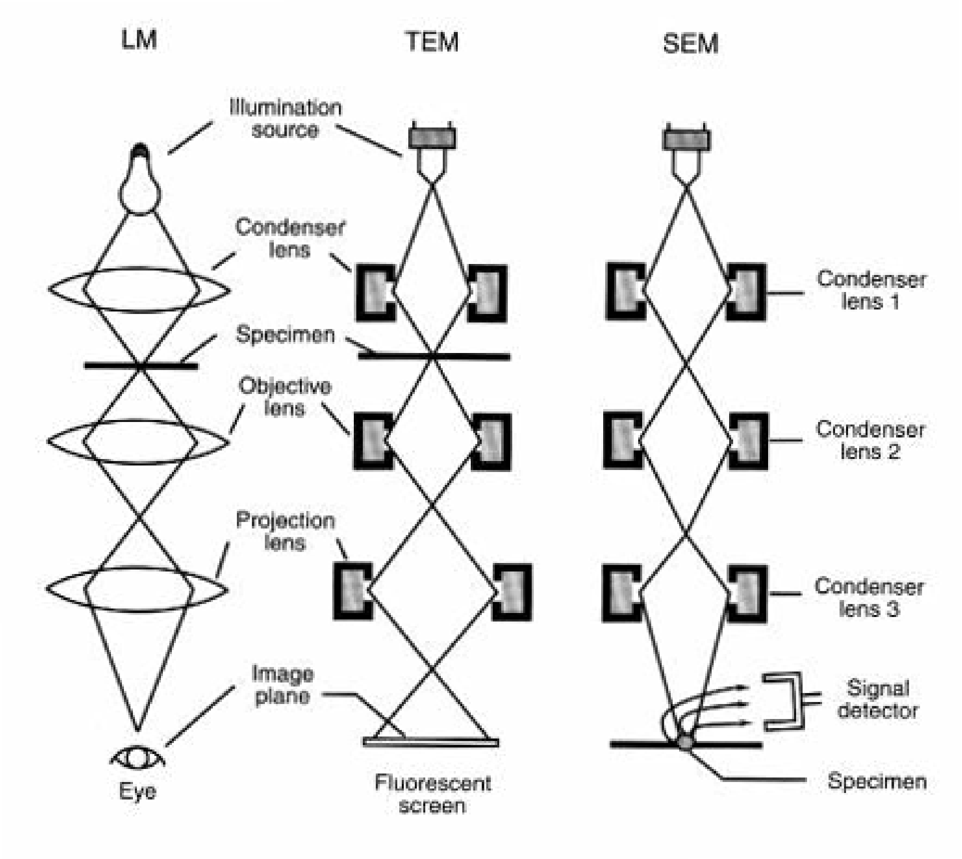

Figure 2: Organisation of Light Microscope (LM), Transmission Electron Microscopy (TEM) and Scanning Electron Microscope (SEM). The University of Iowa (http://www.uiowa.edu/~cmrf/methodology/tem/index.html, accessed 21 January 2014)

Conventional TEM uses only the transmitted beams *or* some of the forward scattered beams to create a diffraction contrast image. Instead, high resolution transmission microscopy uses the transmitted *and* the scattered beams to create an interference image. TEM must have a high performance by low spherical aberrations and high stability of the high tension, of the lens currents and of the energy of the electron beam. The understanding of the image formation must take into account the two following stages:

(1) the propagation of the incident wave through the object;

(2) the transfer of the scattered wave by an optical system of the microscope (the objective lens).

Hence, a TEM produces a high-resolution from the interaction between samples and energetic electrons in the vacuum chamber.

Bendersky and Gayle (2001, p. 997) argue that:

> A great advantage of the TEM is the capability to observe, by adjusting the electron lenses, both electron microscope images (information in real space) and diffraction patterns (information in reciprocal space) for the same region.

TEM is the most powerful magnification with over one million times and yields information of the surface features, shape and structure. For this reason, TEM is an apt instrument to support scientific research in nanotechnology (Kostoff *et al.,* 2008; Schmidt, 2008; Coccia, 2012), cancer research, materials science, semiconductor research, metallurgy, and so on.

The electron diffraction, associated to TEM, is adopted for phase identification, structure and symmetry determination, foil thickness measurement, lattice parameter measurement, disorder and defect identification as well as to solve crystallographic problems. Electron diffraction *via* the transmission electron microscope (TEM) is a potent method for characterising the structure of materials, including perfect crystals and defect structures. The advantages of electron diffraction over other methods, *e.g. X*-ray or neutron, arise from the extremely short wavelength (≈2 pm)[17], the strong atomic scattering, and the ability to examine tiny volumes of matter (≈10 nm^3; *see* Bendersky and Gayle, 2001). Convergent beam electron diffraction has supported the discovery and characterisation of new structures, alone and associated to other diffraction methods (*cf.* Bendersky and Gayle, 2001, pp. 999-1003).

In short, specific lab-oriented radical technological innovations can play a vital role to support the scientific research, such as the TEM that has been a main technological determinant of the discovery of quasi-periodic materials. This argument is underlined by

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[17] A picometre (pm) is a unit of length in the metric system, equal to one trillionth (i.e., $^1/_{1,000,000,000,000}$) of a metre.

Shechtman (2012) in the distinguished lecture and a personal oral communication in this occasion. In fact, the TEM revealed a structure in the scientific investigation of phases formed by rapidly-quenched aluminium alloy that before was not possible (*cf.* Bendersky and Gayle, 2001). In particular, electron diffraction *via* TEM displayed that icosahedral phase has 5-fold rotational axes and it was not periodic (*e.g.* a pseudo five-fold rotation symmetry from a twinned Al-Fe periodic crystal). This main breakthrough is produced by TEM, which has improved the performance and capabilities of researchers in the scientific research process and, as a consequence, has driven a vital scientific paradigm shift in crystallography.

4.1 A statistical evidence: The diffusion of Transmission Electron Microscopy and Electron Diffraction as critical background for breakthroughs of quasi-periodic materials

The case study of Transmission Electron Microscopy (TEM), analysed in previous section, is a strong evidence to validate the HP. The following empirical evidence further supports the HP and confirms the vital role of the diffusion of the TEM to develop the research field of Quasi-periodic crystals (QCs). Data, based on combined keywords concerning TEM and QCs, are retrieved in Scopus[18] (2013). They are 259,960 occurrences of scientific articles in specific research fields.

First of all, the main subject areas of the scientific research by TEM and electron diffraction are in Table 1.

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[18] Scopus is a bibliographic database containing abstracts and citations for academic journal articles as well as patent databases. It is owned by Elsevier.

Table 1: Main subject areas of TEM and Electron Diffraction (1974-2011)

Subject Area	Documents	%
Materials science	7,560	38.24
Physics and Astronomy	6,073	30.72
Chemistry	2,546	12.88
Engineering	2,376	12.02
Chemical Engineering	938	4.74
Biochemistry, Genetics and Molecular Biology	277	1.40
Total	**19,770**	**100.00**

Source: Scopus (2013)

Table 2 shows the main subject areas of the scientific research of Quasi-periodic crystals (QCs).

Table 2: Main subject areas of Quasi-periodic crystals (all years)

Subject Area	Documents	%
Physics and Astronomy	3,234	40.71
Materials science	3,148	39.63
Engineering	887	11.17
Chemistry	386	4.86
Biochemistry, Genetics and Molecular Biology	102	1.28
Computer science	101	1.27
Chemical Engineering	86	1.08
Total	**7,944**	100

Source: Scopus (2013)

Table 3 shows the main subject areas of the association between scientific research in Quasi-periodic crystals and TEM. This table 3 confirms previous results.

Table 3: Main subject areas of combined keywords: Quasi-periodic crystals and TEM

Subject Area	**Documents**	**%**
Materials science	456	60.08
Physics and Astronomy	193	25.43
Engineering	83	10.94
Chemistry	17	2.24
Biochemistry, Genetics and Molecular Biology	4	0.53
Chemical Engineering	6	0.79
Total	**759**	**100**

Source: Scopus (2013)

Trends of phenomena show the fruitful linkages between TEM and QCs. In particular, trends have a considerable temporal acceleration: TEM and Electron Diffraction have a peak in 2004 (*see* Fig. 3 and Fig. 4), whereas QCs have a peak over 2000-2004 period (Figure 4).

Figures 3 and 4 also show a linear regression model[19], estimated by ordinary least squares (OLS) method: in particular, Fig. 3 displays that an additional year increases the expected number of articles concerning TEM (Electron Diffraction) by somewhat more than 416 (55). The R^2 of the estimated model implies that more than 84% of the variation in number of articles can be attributed (linearly) to the temporal evolution. *Mutatis mutandis*[20] in Figure 4.

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[19] The estimation of a linear relationship is based on the following model: $Y_i=\alpha+\beta T_i+\varepsilon_i$; $i=1, \ldots, n$ (T=*Time;* ε_i=Errors).

20 *Mutatis mutandis* is a Latin phrase meaning: “changing [only] those things which need to be changed”.

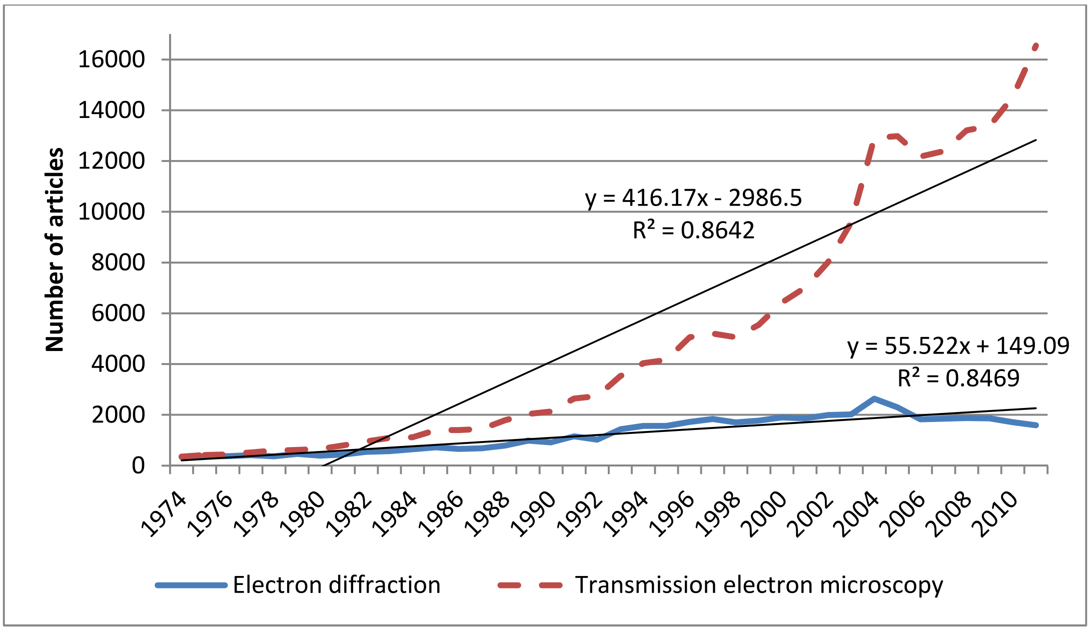

Figure 3: Trends of Electron diffraction and TEM

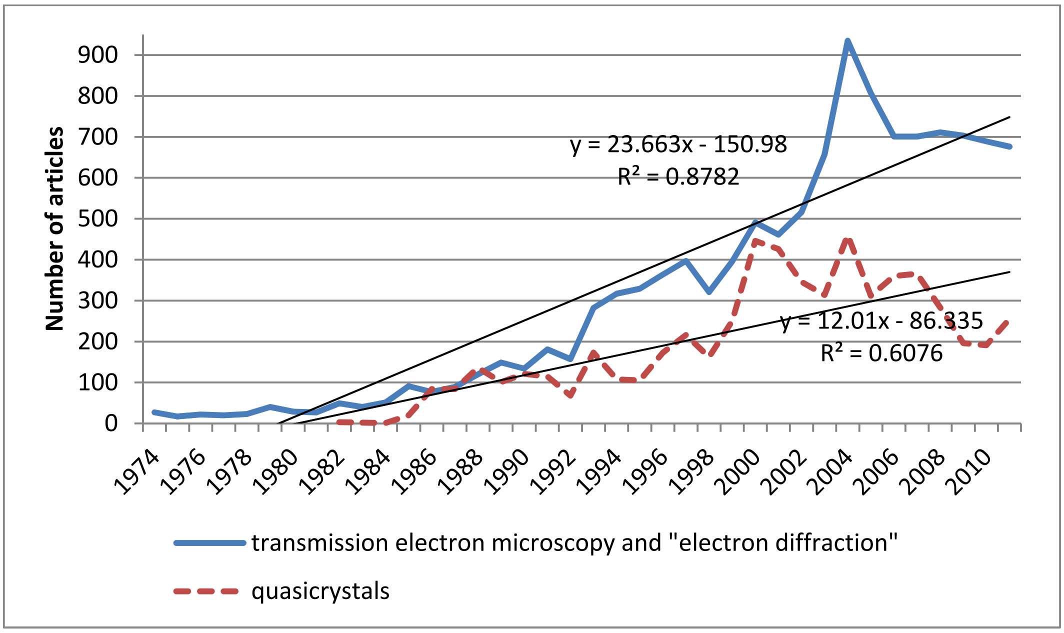

Figure 4: Trends of Electron diffraction and TEM, and Quasi-periodic crystals

A complementary analysis to support the epistemological stance (HP) is based on citations. Total number of *citations* of TEM and Electron diffraction, on Data of Scopus (2013) over <1998-2012, is about 191,864. Figure 5 shows a growing linear trend of citations from 1998 (first year available in Scopus); in addition, linear regression model shows that an additional year increases the expected citations concerning TEM and electron diffraction by somewhat more than 1454 (*citations*). The R^2 of the estimated model is 92.5%, which implies that more than 92% of the variation in citations can be attributed (linearly) to the temporal evolution.

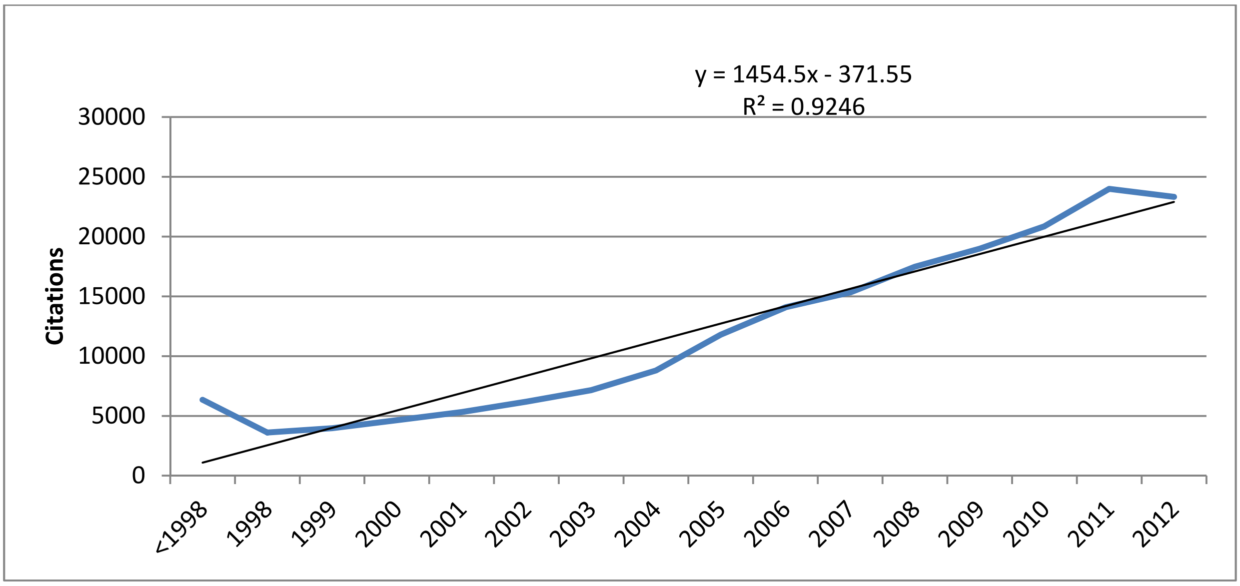

Figure 5: Trend of Citations in the research fields of TEM and Electron diffraction

Instead, total number of citations of Quasi-periodic crystals over <1998-2012 is about 62,676 (Scopus, 2013). Figure 6 shows a growing linear trend of citations from 1998 onwards; in this case too, the linear model indicates that an additional year increases the expected citations in this new research field of QCs by somewhat more than 217 citations. The R^2 (coefficient of determination) of the estimated model is high: 75%.

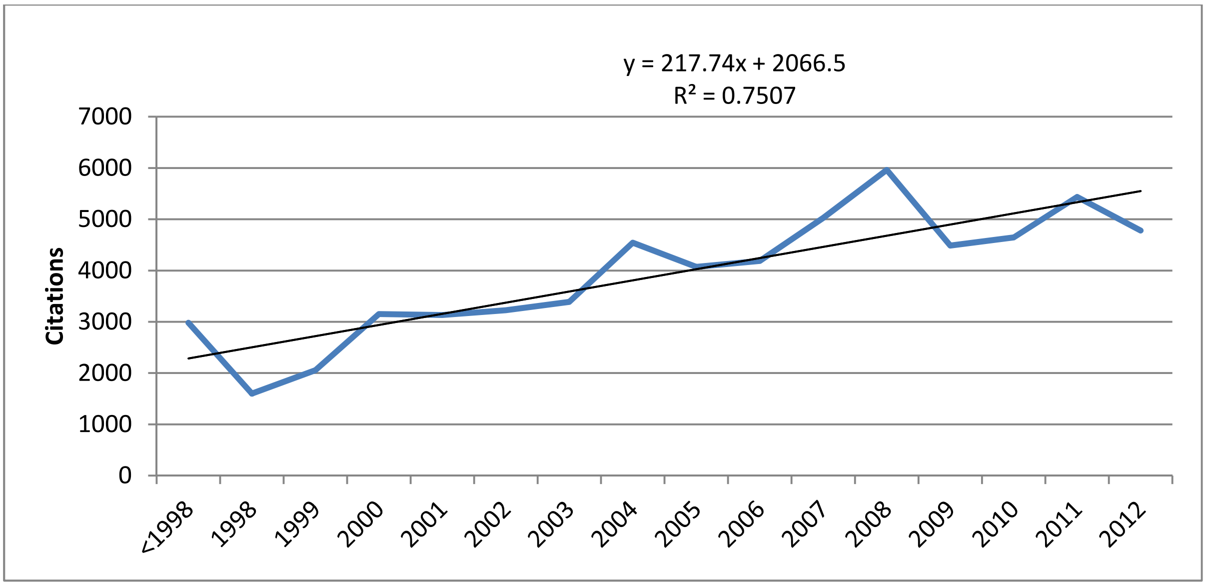

Figure 6: Trend of Citations in research fields of Quasi-periodic crystals

Total number of citations of the combined keywords "Quasi-periodic crystals" and "TEM", over <1998-2012, is about 6,492 (Scopus, 2013). Figure 7 shows a non-linear curve (*concave downwards*) of citations from 1998 onwards; peak of citations is in the intermediate zone 2004-2007; beyond this time span, the citations start to decrease (about 20 years later the discovery of Quasi-periodic crystals). This non-linear pathway tends to generate decreasing returns of knowledge in the production of new knowledge in these research fields; this result may be due to lower chance and incentives over time by scholars to introduce new findings as the result of previous fruitful breakthroughs and scientific discoveries (*cumulative learning*). The goodness of fit (R^2 = coefficient of determination) of the model is about 65%.

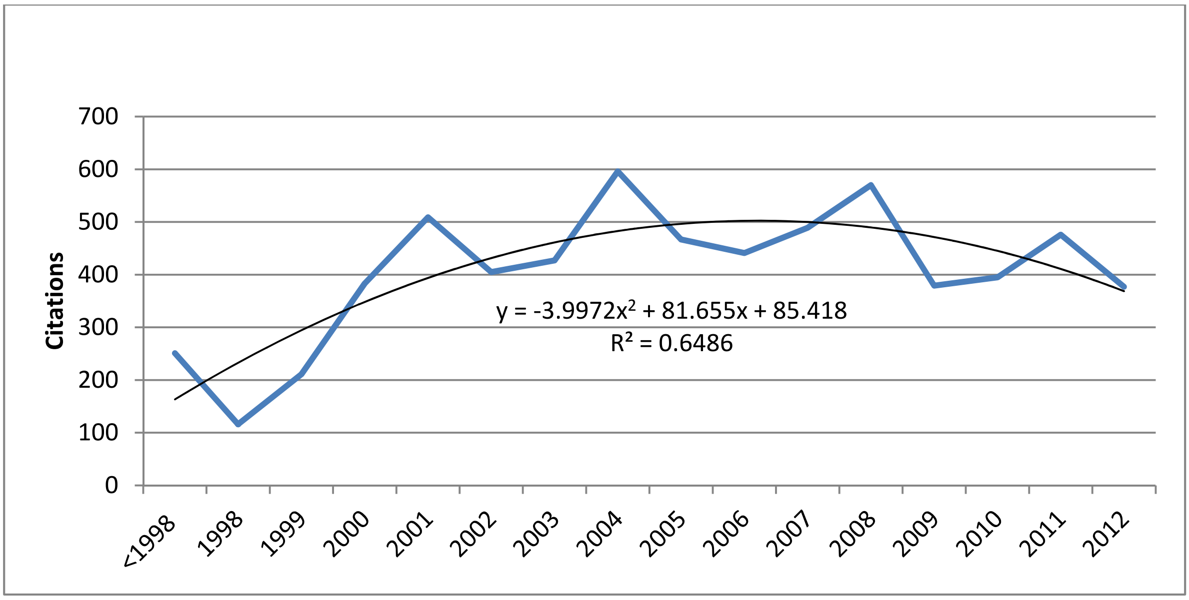

Figure 7: Non-linear trend of citations in the research fields of Quasi-periodic crystals and TEM

In order to confirm the evidence that the technological diffusion of the TEM is the background, which lays the foundation for the discovery of QCs, the rates of growth of specific trends are calculated. Data have an apt structure to apply an exponential model (*cf.* Coccia, 2014b).

The *assumptions* are:

- P_0 is the number of articles in the specific research field at the initial year (*e.g.* 1974);
- P_t is the number of articles in the specific research field at the final year (*e.g.* 2011);
- *t* is the period analysed;
- Articles are a proxy of the scientific activity in specific research fields.

The model, thereby, is given by:

$P_t = P_0 \cdot e^{rt}$ where *e* is the base of natural logarithm (2.71828…)

Hence $\dfrac{P_t}{P_0} = e^{r\,t}$

$$Log\,\frac{P_t}{P_0} = r \cdot t$$

$$r = \frac{Log\left(\frac{P_t}{P_0}\right)}{t} \qquad [1]$$

r= rate of scientific and technological advances

This model is helpful to measure and assess the evolutionary growth of knowledge and can offer an analytical framework for understanding the technological diffusion of TEM that has played a critical role for supporting breakthroughs in QCs discovery.

Eq. [1] shows that the rate of scientific growth of TEM in the 1974-1982 period is high and equal to 10.9% (Tab. 4). This rate expresses the accumulation of scientific and technical knowledge of TEM applied in several scientific fields. Instead, the rate of scientific growth of combined keywords (*i.e.* TEM and electron diffraction) is higher in 1983-2011 period (r=9.75%), after the scientific discovery of QCs (in fact, it was 6.62% over 1974-1982). This result may be due to the high interest in the novel research field of QCs, after the discovery in 1982, when the scholars focus on an intensive research activity to support breakthroughs in this new scientific pathway.

Table 4: Rate of scientific growth of keywords concerning TEM and Quasi-periodic crystals

	r= rate of scientific advances of the knowledge (Eq. [1])				
Description	**%**	1974-1982 **%**	1983-2011 **%**	1974-2011 **%**	Sum of articles
• Electron diffraction				4.06	46,807
• Transmission electron microscopy		10.90	9.37	10.09	194,892
• Transmission electron microscopy and electron diffraction		6.62	9.75	8.47	11,797
• Quasi-periodic crystals 1982-2011	**5.14**				5,877
• Quasi-periodic crystals and transmission electron microscopy 1986-2011	**14.75**				587
				Total	**259,960**

Note: These are rates of scientific advances based on Eq. [1]

In addition, the acceleration of scientific outputs of QCs and TEM, over 1986-2011 period, is higher (14.75%) than QCs alone (≈5%). This is likely due to the intertwined relationship between TEM and the new scientific field of QCs.

This empirical evidence confirms the vital interaction of electron diffraction *via* TEM (*lab-oriented technological innovations*) and the research field of QCs. In particular, these results show that electron diffraction *via* TEM has played a main role as scientific background and driving force for breakthroughs of QCs in crystallography. In addition to case study research, these empirical findings further tend to validate the HP and lay the foundations for developing a main theoretical framework between observed facts.

5. Technological Analysis: characteristics and properties of lab-oriented radical innovations for scientific discoveries

The detected key building blocks and linkages of this study can be schematically summarised in the inductive schema of Figure 8.

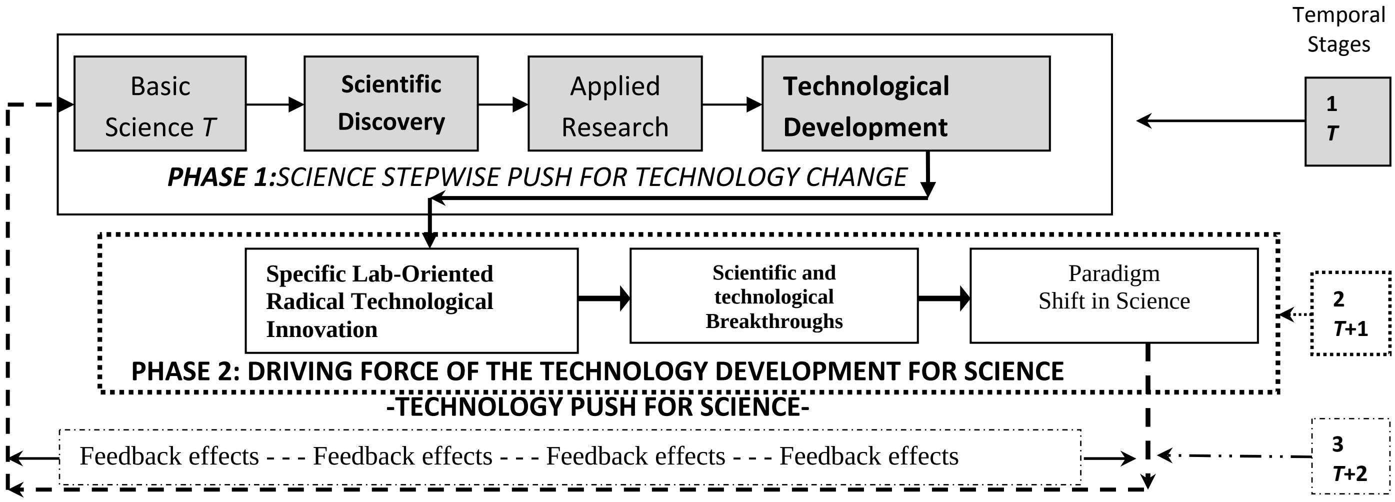

Figure 8. Interaction for continuous progress of science and technology (*Note*: *T*=time)

In particular, the analysis of this study can explain the nature of lab-oriented radical innovations and connections that run from technological development to breakthroughs and scientific paradigm shift (*T*+1), with fruitful feedback effects (*T*+2).

- *SCIENCE STEPWISE PUSH FOR TECHNOLOGY CHANGE*

The technological progress can be generated by a linear model that assumes the stepwise progression from scientific discoveries in basic science, through applied research, to technological development. Rothwell (1994, p. 40*ff*) states that: " 'More R&D in' equalled 'more innovation out' " (*cf.* Coccia, 2012a). Instead, Clark (1987, p. 36) argues that technological development is clearly "heavily influenced by science" and Bunch and Hellemans (2004, p. 436) claim that: "There are enough examples of recent technological developments, such as the transistor or the laser . . . . The development of radio communications is an early example of the direct application of physics". However, Gibbons and Johnston (1974) stress the weakness of the linear model and the importance of informal links within the relationship between science and technology.

- *SPECIFIC LAB-ORIENTED RADICAL TECHNOLOGICAL INNOVATIONS AS DRIVING FORCES OF SCIENTIFIC DISCOVERIES –THE TECHNOLOGY PUSH FOR SCIENCE*

Technological change engenders different technological innovations: incremental, radical, technological system, enabling technology and change of techno-economic paradigm (the latter has the highest degree of impact on geo-economic system; *see* Coccia, 2005a, p. 122*ff*). Radical innovation is a main element of the technological change, which generates a drastic impact on socio-cultural-economic system (Coccia, 2005a, p. 123)[21]. There can be different typologies of radical innovations in relation to adopters and users. This study pinpoints (Fig. 9):

- user-friendly radical innovation (such as iPod, iPhone, contact lens, etc.). This has a broad diffusion across population and is defined as a radical innovation of Second (II) degree in the hierarchy because it does not affect scientific research and scientific progress;

- *not* user-friendly radical innovation (sophisticated scientific instruments, such as positron emission tomography scanners, the Spitzer Space Telescope, TEM, etc.). This is originated (driven) by a theoretical scientific problem of basic science (*e.g.* the study of

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[21] Coccia (2005a, p. 123) argues: “Fifth-degree innovation: strong. Radically new innovations that occur discontinuously over time. A new product is born. According to Abernathy and Clark, the basic configuration of the product is redefined. A new technological paradigm is born, a fundamental need is satisfied, and a new market is born.

- Consumer: Meets a need, which has not yet been fulfilled, and/or creates a new one. The innovation improves the lifestyle of the adopter/consumer, increasing the general level of well-being.
- Firm: The market share of the firms is changed with the arrival of new firms. These firms are defined by Freeman and Soete … as aggressive and belong to the science-based sector according to Pavitt’s … taxonomy.
- Market: A new sector is created”.

the stars and moon by Galileo and other scholars that invented the telescope). A long-run process of convergence and development of basic science, applied research (engineering) and technological innovations context-dependent (*e.g.* astronomical issues and development of the optics) engenders specific radical innovations to support scientific research (*e.g.* telescope). This specific radical innovation is mainly adopted in research laboratories with high-skilled human capital in basic and applied sciences (*i.e.* researchers) and tends to spur scientific discoveries (*cf.* Sung and Hopkins, 2006; Almirall and Wareham, 2011). This is radical innovation of First (I) degree in the hierarchy in terms of fruitful impact on scientific discoveries (Fig. 9).The latter specific radical technological innovation is defined as *lab-oriented radical innovation* that needs high technical skills to be used (*i.e*. high-skilled users: researchers). These lab-oriented radical innovations tend to be a main determinant of breakthroughs and scientific discoveries (*Technology Push for Science*).

In particular, the lab-oriented radical innovations can support the progress of science in groundbreaking research fields because they provide advanced instruments/approaches to find a solution to relevant scientific problems and/or to detect scientific problems. In addition, they can also support positive feedbacks for spurring further radical innovations user-friendly. Hence, in general, the fruitful linkage running from technology to science generates a continuous progress that enhances the knowledge of societies.

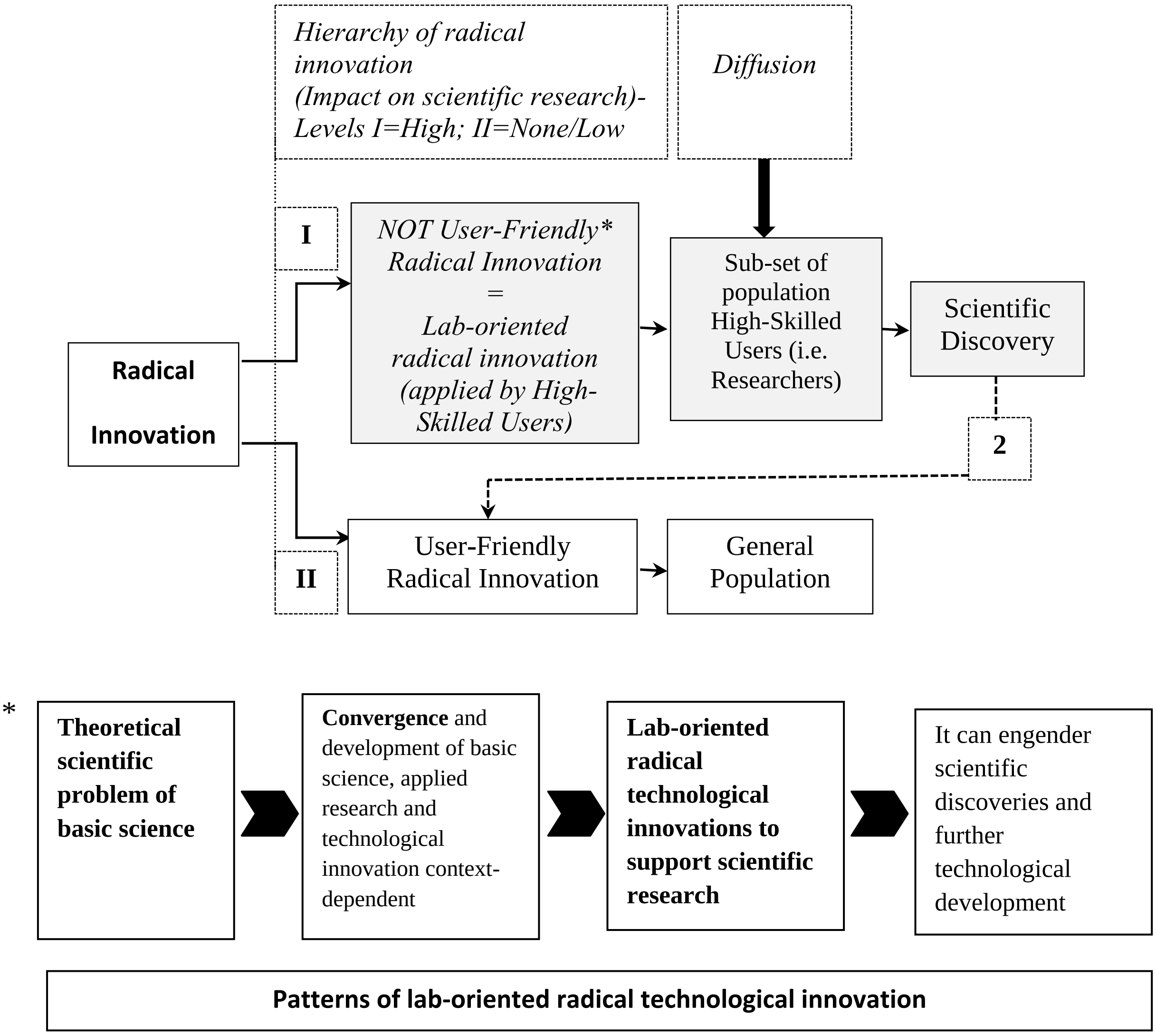

Figure 9. Types of radical innovation

The present study validates the HP by analysing a main case study that shows the vital role of the lab-oriented radical innovation, Transmission Electron Microscopy (TEM), which has supported the discovery of Quasi-periodic crystals and, as a consequence, a critical scientific paradigm shift in crystallography.

A main question is:

What are the main characteristics of these specific lab-oriented radical technological innovations, such as TEM, that spur scientific discoveries?

The characteristics following are all necessary conditions to characterise their systemic relevance for scientific research and discovery process.

- The first main characteristic is that these specific technological innovations are high-tech and complex instruments apt to research at the frontier of scientific knowledge.
- The second main characteristic is that they are adopted by high-skilled users with competences in basic and applied sciences (*e.g.* physicists, biologists, chemists, etc.).
- The third one is that they are mainly applied in research laboratories.
- The fourth one is that they are a means to increase performance and capabilities of researchers in the discovery process: *Maximise the scientific throughput*.

In particular, the case study shows that the TEM is a powerful instrument for characterising the structure of materials and as a consequence for supporting scientific research in crystallography. In fact, TEM is the most powerful magnification to yield scientific information of the surface features, shape and structure. Hence, this specific lab-oriented radical innovation (i.e. TEM) is prone to support scientific research in nanotechnology, genetics, materials science, semiconductor research, metallurgy, and so on.

The main properties of these *specific lab-oriented radical innovations (LABORINs)*, which support discovery process and scientific discoveries, are:

- *Optimisation of discovery process. LABORINs* support *rational modes* of users within scientific discovery processes by developing and increasing performance and integrative capabilities of researchers (*cf.* Henderson, 1994, p. 607ff);
- *Increase of learning process and metabolism of scientific knowledge. LABORINs* improve the *learning process and metabolism* of scientific knowledge in discovery processes,

supporting patterns of ground-breaking research fields and, as a consequence, likely vital breakthroughs;

- *Acceleration of the discovery process. LABORINs accelerate the discovery process* by a rapid development of effective knowledge to achieve scientific goals and discoveries. In addition, they reduce the time within research stages (Target identification, Assay development, etc.) due to faster and deeper scientific investigation that favours a higher and intensive cumulative learning that drives findings in new research fields;
- *Collective learning within research laboratories. LABORINs* amplify *collective learning* within the research lab and spur multiplicity of stimuli during the discovery process to achieve scientific goals and/or to solve problems; this role in the learning process reinforces the ability to identify and control key elements of the discovery process so that knowledge can be successfully accumulated to produce effective 'know-how' " (*cf.* v. Tunzelmann *et al.* 2008, p. 479; Almirall and Wareham, 2011; Mirabeau *et al.,* 2014));
- *Learning via diffusion*: The increased adoption of these specific innovations (*LABORINs*) paves the way for improving its characteristics and efficacy in scientific discovery processes (*cf.* Sahal, 1981, p. 114);
- *Support to scientific objectives of researchers,* i.e. *LABORINs* support the '*interest and goals' of professional 'knowledge-seekers*' (cf. Clark, 1987), increasing performance and capabilities of these users in the discovery process: Maximisation of scientific throughput;
- *Uncertainty*. *LABORINs* tend to have *uncertainty* on discovery process in terms of impact and timing to achieve the scientific goals and discovery.

These basic properties of *lab-oriented radical innovations* (*LABORINS*) can be schematically represented by the inductive chart in Figure 10.

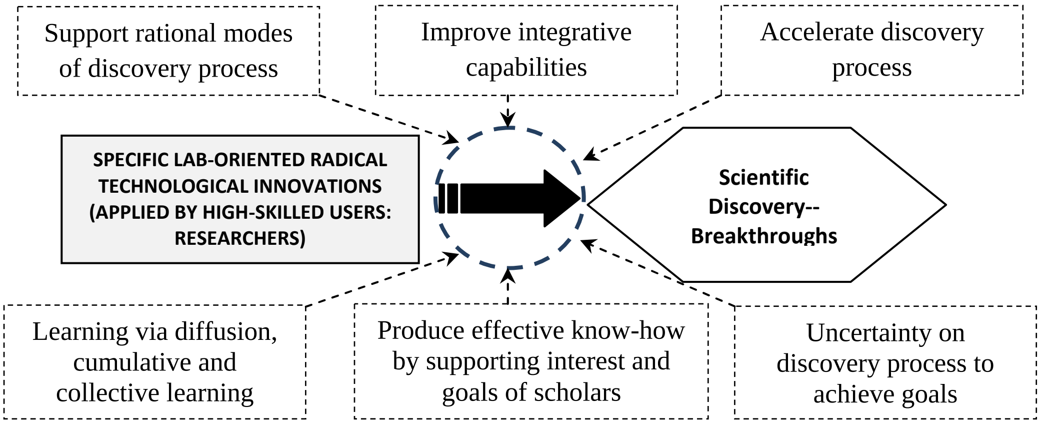

Figure 10. Basic properties of lab-oriented radical innovations that spur scientific discovery

6. Concluding observations

Lab-oriented radical innovations are "an intrinsic part of technological activity" (Clark, 1987, p. 34) because they play a main role in the technology change and have a main impact on scientific progress. Unlike user-friendly radical innovations, widely diffused across population, the study here has detected the systemic and driving role of *specific lab-oriented radical innovations* (*i.e.* applied in research labs by high-skilled users: researchers) for supporting the discovery process to engender effective knowledge and vital scientific discoveries. The evidence of this study tends to support the HP that the scientific progress (based on discoveries) is also driven by key lab-oriented radical technological innovations that enable the development of breakthroughs. In fact, the case study shows that the imaging by TEM has provided a vital evidence to engender the discovery of QCs (*cf.* Darby and Williamson, 2011). The findings of the present study are systematised in a basic framework that explains key elements, linkages, characteristics and properties of the lab-oriented radical innovations that drive the fruitful linkage running from technological change to progress in science.

Socio-economic relations also play a main role for the development and utilisation of these specific radical innovations in the discovery process. In fact, scientists tend to "adopt once they see enough empirical evidence to convince them that innovation is worth adopting" (Young, 2009, p. 1900, *passim*). Clark (1987) argues that there are interesting comparabilities between scientific and technological paradigms. In particular, science and technology have a continuum of knowledge flow produced under two competing forces: "Knowledge-seeking continuum guided by two overriding sets of forces –those relating to markets for goods and services on the one hand, and those relating to the 'interest and goals' of professional 'knowledge-seekers' on the other" (Clark, 1987, p. 40, original emphasis).

In general, technological and scientific paradigms have a fruitful interaction that provides the basis for heuristic development. As a matter of fact, new technological paradigm based on lab-oriented radical innovations can be a main propellant of scientific growth either in itself or in combination with other paradigms, by supporting "metaevolutionary" patterns (Sahal, 1981) of the scientific research that spur vital discoveries. However, it is important to remark that the origin of a scientific discovery and the development of a paradigm shift in science are driven by complex mechanisms based on several socio-cultural-economic factors, and technological innovation is only one of these main determinants.

To sum up, the study here provides an interesting theoretical framework that explains some characteristics and properties of specific radical innovations, defined *lab-oriented radical innovation, adopted by high-skilled users,* which can enable the progress in science.

Nevertheless, frameworks concerning patterns of technological innovation are problematic because radical technological innovations can have an infinite set of consequences such that no rule will be true in all situations, in particular when we know that other things are often not equal in current turbulent and fast-running technological change.

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