Burmaoglu, S., Porter, A.L., & Souminen, A. (2018), What is technology emergence? A micro level definition for improving tech mining practice, *Portland International Conference on Management of Engineering and Technology (PICMET),* Honolulu.

WHAT IS TECHNOLOGICAL EMERGENCE? A CONCEPTUAL FRAMEWORK

Abstract

Keywords: emergence, technological emergence, concept, review, emerging technology, emerging

INTRODUCTION

Technological emergence has been subject to scholarly works since evolutionary economists put technology in the center of development. Especially after Solow (1957)'s case for the limited explanatory power of neoclassical principles, knowledge has been understood as an additional factor of production. Then, technological, organizational, and institutional changes were viewed by evolutionary economists as the core drivers of economic growth. In this respect, economic emergence became popular for decision makers to transform "unknown unknowns" to "known unknowns" by examining historical time series data, that can be accepted as a more powerful explanation of the present than a hypothesis based solely on logic.

Thereafter, identifying, tracking and conceptualizing emerging ideas became popular research subjects in late 20th century literature. At first, the emergence concept arose in science, especially in biology, chemistry and physics. Then, emergence became a popular theme in philosophy of science at the end of the 19th century with discussions on the nature of emergence.

??sorry, I've mangled this. First paragraph seems to start with 1957 Econ. But 2d paragraph is back in 1800s?

These discussions have been found itself useful with developments in evolutionary science??. Increasing understanding of the phenomena in philosophy attracted different scientific groups. For instance, these discussions inspired complexity researchers to examine emergence in complex systems since the 1930s. Complexity theorists also tried to explain different aspects of the emergence concept with self-organizing and synergistic characteristics. In addition to philosophy of science scholars and complexity theory researchers, economists also discussed the same concept from an evolutionary economics perspective (??refs). Some economists asserted that evolutionary perspective was different from biological sciences, emergence concept interpreted in economics with considering philosophical discussions and complexity explanations after 1940s??.

As briefly reviewed, on-going discussions on understanding emergence have progressed in three main academic streams. In all these, emergence concepts have been interpreted by considering their inherent dynamics. This study aims to interpret emergence in a technical/technological context, considering its aspects and applicability.

A number of studies have sought to conceptualize (Alexander, Chase, Newman, Porter, & Roessner, 2012; Rotolo, Hicks, & Martin, 2015; Small, Boyack, & Klavans, 2014) and model (Chen, 2006) the nature and properties of emerging technologies. Moreover, while conceptualizing and modeling technology, many phrases have been introduced in the literature for interpreting technological change; these include: “emerging technologies,” “disruptive technologies,” “innovation”, “invention” and so on. Teran (2017) explained differences and similarities of these concepts by evaluating them from a philosophical perspective. Based on his findings, it can be assessed that “emerging technologies” concept has been different from others with its understanding by other disciplines (Teran, 2017) and it is thought that, the concept is mostly used with its dictionary definition which may degrade its actual understanding??. However, these efforts mostly treat identifying, tracking and forecasting emergence without pursuing the nature of emergence and its aspects. They mostly focused on technological domains whether they were demonstrating emerging/disruptive technological characteristics or not. From this aspect, it can be asserted that these studies dealt not with emergence properties, but with resultants of emergence. For instance, emerging technologies explained by Rotolo et al. (2015) with some resultant aspects and implied that emerging technologies can be examined in detail with the proposed descriptors. However, these descriptors were not discussed whether they can be applied as predictors or not for identifying emergence in technological context.

Another criticism of these studies is a micro-macro level mismatch. In these studies, it can be asserted that researchers tried to understand the whole with examining the parts in detail. In fact, this assertion was contradicting with Anderson’s words as whole was not only different but also very different from the sum of the parts (P. W. Anderson, 1972). Hence, what should be accepted as whole in technology domains or scientific publications/patents is another gap in the literature??.

Considering these gaps, I seek to answer three main research questions:

1. What are the antecedents and consequences of technological/technical emergence?
2. In which stage of scientific and technological change should emergence be expected?
3. How can the micro, meso and macro levels best be defined in technical/technological emergence research?

By answering these questions and combining them with an applied perspective, I propose a process-based model for dealing with technical/technological emergence. In the second section, the theoretical background of emergence is reviewed by elaborating different perspectives and the aspects of emergence put forward with an abstraction??. Then, scientific and technological change models are reviewed for interpreting different aspects of emergence with the cyclic and evolutionary models in third section. After establishing the presence of emergence in scientific and technological change models, in the fourth section, technological emergence is explained as a process and a model proposed with discussing its theoretical foundations. At the same time, a research methodology is proposed for technological emergence detection. Finally, findings are summarized and discussed in the conclusion section.

THEORETICAL BACKGROUND OF EMERGENCE CONCEPT

In this chapter, the emergence concept is reviewed from perspectives of philosophy of science, complexity theory, and evolutionary economics. Figure 1 offers a schematic image of the approach.

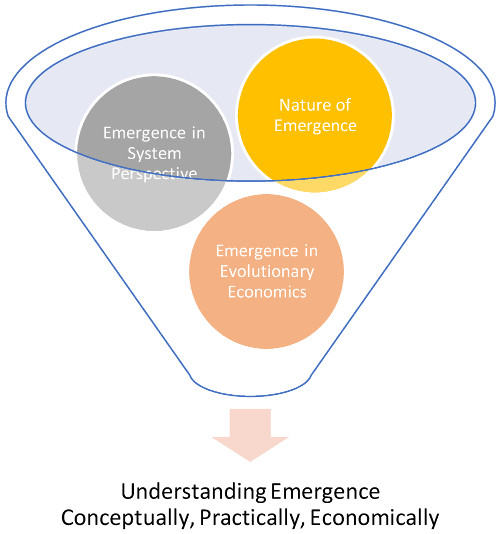

Figure 1 Reviewing Emergence with a Deductive Approach

As can be seen in Figure 1, nature of emergence is searched by reviewing philosophy of science literature, and practical side of emergence is examined with literature of complexity theory [this is not clear?? I can buy 3 key literatures: philosophy of science, complexity science, evolutionary econ; I don't understand how those translate to Conceptual, Practical, Economic. Fig. 1 should clarify that, I think.]. Then, economic aspects of emergence are analyzed with reviewing evolutionary economics perspective. This approach is applied because by applying this methodology it is assumed that; (1) The nature of emergence can be understood and the term may be conceptualized with considering discussions in philosophy of science; (2) Emergence as a part of a complex system can be understood with the applications and discussions in complexity theory research; (3) Emergence in a technological context can be interpreted by examining the views of evolutionary economists.

Emergence concept has been a discussion subject of philosophy of science since 1800s. Sawyer (2001) predated emergence concept to 1875 (Goldspink & Kay, 2010) and expressed that the term was first coined by George Henry Lewes for distinguishing the resultants and emergents in Hume's theory of causation (can you give an illustration distinguishing resultant and emergent??) . Stephan (1992) divided 'emergence' discussion in philosophy of science to four periods. First period was in the last century including the works of John Stuart Mill, Alexander Bain, and George Henry Lewis. Second period came off in the early twentieth century and concerned the attempt to offer an alternative to mechanism and vitalism by introducing a third theory called emergentism with seminal works of Samuel Alexander (Space, Time and Deity, 1920), Lloyd Morgan (Emergent Evolution, 1923), C.D. Broad (The Mind and its Place in Nature, 1925). Sawyer (2001) added Whitehead to second period and asserted that with Morgan they were the pioneers of British emergentism and rejected vitalism and dualism, accepting the materialist ontology that only physical matter existed. Third period was 1940s and in this period there were discussions on emergentism with novelty and non-predictability aspects by W.T.Stace, P.Henle, and G.Bergmann. The third period was also described with the studies on philosophers of mind by cognitivist rejection of behaviorism. This rejection conveyed a discussion with individualists' "mind is nothing more than the biological brain" proposition versus dualists' "mind and brain are distinct". Fourth period was defined by Stephan (1992) with the 1970s and he defined this period with discussion on psycho-physical problems of emergence. Sawyer (2001) furthering this time frame to 1990s and described with studies which were focusing on core concepts in computational modeling of complex systems including connectionism, artificial life, and multi-agent of social systems subjects. It can be seen in literature that 2010s may be accepted as a fifth period of emergence discussions with re-emergence of emergence articles.

[??what should the reader make of all that?]

Beyond its chronological development, it can be asserted that "emergentist" philosophy understands the term 'emergence' differently. At first emergentist theories make statements about the world with three aspects as: its current state (or "being") – the synchronous aspect; its historical development; and evolution (or "becoming") – the diachronous aspect. The synchronous aspect can be characterized by the idea that a whole can have genuinely different properties than parts. It should be noted that some properties of a whole cannot be explained by deducing it from the properties of parts and such properties are called emergent, as opposed to resultant properties. In this sense, P. W. Anderson (1972) emphasized that the whole is not greater than but very different from the sum of parts and suggested that the emergence had a strongly ontological dimension. Morrison (2015) thought that this suggestion had its basis in physics when the examples of emergence in Physics were analyzed. In addition, Morrison (2015) expressed that the most important feature in characterizing the micro/macro relation in emergence is the notion of autonomy and the supposed independence of these two levels in explaining emergent behavior. [seems important; can this relate to our R&D metrics??]

The diachronous aspect deals with the appearance of new things with new properties over time. In this perspective, qualitative novelty is important for this appearance. It is thought that these new properties cannot be predicted from even perfect knowledge of the old properties. It can be assessed that this aspect would distinguish emergent from resultant. Moreover, it should be emphasized that emergentism is interested in qualitative change not just quantitative change and the relation between parts and whole is of central importance in this perspective.

Emergentists saw world in a hierarchy which was structured in higher and lower layers of existence and they thought that emergent properties anchored in structures and didn't exist independently of them. This aspect made emergents not be reducible to them.

According to Pepper (1926) emergence would signify a kind of change. Based on his description this change occurred in three different ways as the assertion of a cosmic irregularity; a shift by which one characteristic replaces another; cumulative change in which certain characteristics supervene upon other characteristics. Then, he emphasized that the emergent evolutionists should admit a thorough-going regularity in nature. Actually, Corning (2002) supported this idea by emphasizing Darwin's quote of the "Law of Continuity" implying an incremental nature to evolutionary change. From this aspect, it can be expressed that "continuity," "unexpectedness" and "uncertainty" are important dimensions of detecting emergence when the subject is approached via an evolutionary perspective.

With Pepper's (1926) discussion and classification, the emergent (is this distinct from emergence??) phenomenon became more popular in conjunction with observed evolutionary shifts in almost all fields of science. The definition of the concept became more significant. Goldspink and Kay (2010) summarized widely agreed upon characteristics of emergent entities as:

(1) being characterized by higher-order descriptions;
(2) obeying higher order laws;
(3) being characterized by unpredictable novelty;
(4) composed of lower level entities;
(5) with lower level entities insufficient to fully account for emergent entities.

[?? How are #1, 2 and 4 different?]

Sartenaer (2015) articulated emergence from a reductionist approach. He first described the working definition of emergence by considering the relation between emergent and its emergence basis [??]. He discussed that emergent might be ontologically determined by its emergence basis and understood qualitatively novel or untraceable. Qualitative novelty was explained in the study as ambiguous expression and untraceable was called failure of determinative traceability??. Even if emergence was thought to be untraceable, J. Kim (1999) proposed that a higher degree of organizational complexity might exhibit novel properties. From this statement it can be asserted that these properties might not be predicted, but they may be expected based on the increasing measure of complexity in organizations or domains. J. Kim (1999) supported a predictability proposition by dividing it into two as inductive and theoretical predictability, and emphasized inductive predictability of emergent properties??.

Because technology context entails features of a social network, the emergence concept should also be examined from a sociological perspective. Goldspink and Kay (2010) differentiated social systems from other fields with human agents' cognitive aspects [??] and emphasized the theory of autopoiesis, which was described as humans coordinating their action by way of communication. They proposed a hologram analogy for describing the whole by considering that removal of every part (agents) may reduce the resolution. This analogy stressed coherence in collaboration networks and pattern formation. Sawyer (2001) emphasized that for all emergentists, [??terminology kills me – do you need these variants on emergence?] interaction is the central issue and asserted that higher-level properties emerge from interaction of individuals in a complex system. The complexity of interaction among components might be another variable contributing to emergence. He also compared individualists and collectivists in his study, and from the collectivist perspective, explained irreducible systems with nonaggregativity, near decomposability, localization, and complexity of interaction characteristics. Sawyer (2001) expressed that most social properties were not aggregative and thus they should be treated as emergent. He further argued that connectionist models suggested that the density of network connections was related to localizability and decomposability of the system and proposed that dynamic density increased as communication and transportation technology advanced.

Discussions on emergence and emergent also inspired complexity theorists from an applied perspective. Wierzbicki (2015) defines the emergence principle from a complexity perspective as "*new properties of systems emerge with the increase of their complexity; these properties are qualitatively different from the properties of parts of the systems and irreducible to them.*" It can be understood from the definition that emergence should contain some aspects that are qualitatively different and irreducible. Moreover, Corning (2002) proposed that emergence can be produced by "self-organizing" processes, and he cited Doyne Farmer's quote for emergence to demonstrate the concept's high ambiguity as "It's not magic… but it feels like magic".

Corning (2002) compared different definitions of emergence from different disciplines and he stated that it was hard to decide on a concrete, compromise definition. However, as Sartenaer (2016) stated, the broader the concept's extension is, the weaker its instructive value is. Therefore, it is crucial to understand and define the concept by stating its aspects.

Corning (2002) proposed synergy as an important aspect of emergence. He defined synergy as "*the combined effects that are produced by two or more particles, elements, parts or organisms- effects that are not otherwise attainable*". He understood synergy from the "functional complementarities" perspective that can ability to affect whole with its new combinations. Therefore, he proposed emergent phenomena as "*a subset of the vast (and still expanding) universe of cooperative interactions that produce synergetic effects of various kinds, both in nature and in human societies".* He added that *"this definition would be limited to qualitative novelties, unique synergistic effects that were generated by functional complementarities, or a combination of labor*". Sawyer (2004) articulated synergism with his proposition that an increasing number of component units may increase the likelihood of emergent higher-level properties. However, Corning's definition should not be understood that all synergistic effect would entail emergence without modifying, reshaping or transforming whole with its participation. Then, he asserted that self-organization may not be necessary for all conditions.

From a different perspective in complexity research, Goldstein (2003) connected emergence to creativity processes. He proposed a thesis that emergent and creative processes shared a common logic of novelty generation. He exemplified this relationship through the use of emergence by scholars as Bergson's "creative evolution", C.L. Morgan's "creative synthesis", Whitehead's "a general theory of creativity" and Prigogine's description of self-organizing emergence as a creative process (Goldstein, 2004). Therefore, tracking creativity processes in knowledge management may lead to identifying and tracking emergent properties. He claimed that radical novel outcomes might be reached after improvising or negation of the past pattern. Hence, it can be thought that a paternalistic approach may suit for identifying radical novelty. However, the qualitative nature of novelty may again prove problematic, needing expert [1] judgment. In judging, expert opinions should focus on newness, originality and changing the potential of pre-existing patterns.

Moreover, it is well-known that creativity in science has collaboration and network characteristics (Y. N. Lee, Walsh, & Wang, 2015). In this sense, Sawyer (2004) proposed an 'artificial societies' concept emphasizing the collaboration and negotiations of autonomous computational agents with each other in a self-organizing fashion. He criticized this concept with its mechanistic perspective but he emphasized the transition from equation-based modeling to agent-based modeling ??can you illustrate?.

[1] Expert was defined in Munier and Ronde (2001)'s study by citing Paradiso as an individual with his/her qualitative and practical knowledge. They emphasized that it was his recognized knowledge, which guided his behavior and his choice between various possible orientations for a given subject.

Goldstein (2002) characterized the levels of emergence with considering it as a new natural kind??. This new kind constructs may appear when science, mathematics, or philosophy would introduce new ways of looking at nature leading to the recognition of regularities not perceived before. This perspective put forward the evolutionary perspective and may be applied to technological context with Fisher-Pry's substitutional trend modeling. New natural kind [??what is this?] becomes dominant in technical and technological context while it has potential to solve the existing technical/technological or societal problems. However, the nature of evolution forces the dominant design repeatedly to transform incrementally -- or radically, unexpectedly and unpredictably.

Goldstein (2004) proposed self-transcending construction (STC) feature for emergence [as criterion??] in his study arguing the relevancy of self-organization in accounting for the emergence of radically new patterns, structures, and properties. He emphasized the pervasiveness of creativity in everyday life and asserted that creativity would be a phenomenon that can be nurtured and encouraged so as to demonstrate a blend of intentional construction and spontaneous inspiration. He furthered his explanations on creativity with its processual logic and asserted that recombinatory creative strategies took antecedent arrangements and changed or negated aspects of it as creative process proceeded.

Like the creativity analogy, Crutchfield (2013) proposed a discovery process analogy and explained emergence as a process that led to the appearance of structure not directly described by the defining constraints and instantaneous forces that control a system. He emphasized "something new" for emergence and discussed 'something' and 'new' in his study separately. In this discussion, he proposed two new features as unpredictability and self-similarity and emphasized the role of newness from the eye of observer. With newness, novelty was also mentioned in his study and he ranged novelty spanning from 'obvious' to 'purposeful' spectrum. Crutchfield (2013) questioned this newness problem in emergence because he posited that it was always referred outside the system to some observer that anticipated the structures via a fixed palette of possible regularities. Finally, he summarized his findings with three notions of emergence as: (a) the intuitive definition of emergence: "something new appears"; (b) pattern formation: an observer identifies "organization" in a dynamical system; (c) Intrinsic emergence: the system itself capitalizes on patterns that appear.

Moreover, Crutchfield (2013) distinguished discovery from emergence with two issues. First, discoveries are atemporal, because the change in state and increased knowledge of the observer were not the focus of the analysis activity, but emergence was dynamical in an evolutionary system. He stated that emergence concerned the process of discovery. Therefore, it can be concluded that understanding discovery process with its dynamics may lead to understand emergence.

J. Goldstein (2013) explained five necessary characteristics of emergence with radical novelty (with considering explanatory gap of emergence??); Coherence/Collective/Wholeness; global or macro level; ostensive; dynamical concepts; and proposed self-transcending constructions (STC) as a feature of emergence that considering emergence phenomenon with a processual perspective[??what are the five?]. He also emphasized that if emergent didn't display that they both followed from and were discontinuous with the substrates from which they emerged, then they didn't warrant being labeled emergent[??example?]. With this assertion, it can be interpreted that continuity may be accepted as an important component while tracking emergence. Carley, Newman, Porter, and Garner (2017) analyzed continuity with a different concept as "persistence," and illustrated for several datasets that research with greater staying power deserved special attention. However, the arguments related the persistence were described with resultant properties while aiming to identify emergence with a predictive approach??. In this aspect, it can be asserted that persistence may not be considered as continuity, as defined by complexity literature when the discussions in the old-new and whole-part relationships were considered (Hofkirchner, 1998).

Evolutionary economics is another academic stream considereding the emergence concept. Evolutionary concept appears in economics with Schumpeter's ideas on the importance of innovation in economic growth and creative entrepreneurship. Boulding's (1991) contributions appear seminal for the contemporary surge in evolutionary economics (Frederiksen & Jagtfelt, 2013). Boulding identified evolutionary economics as '… *is simply an attempt to look at an economic system, whether of the whole world of its parts as continuing process in space and time.[??check this – grammar seems wrong]*' In this respect, it can be asserted that the dynamism made scholars handle economics with evolutionary perspective. However, despite Boulding's definition of evolutionary economics and considerable influence of American Institutionalism (Foster, 2006), Schumpeter rejected applying biological selection metaphors to economics, based on Dawid (2006)'s explanations.

Many studies applied principles of emergence and complexity science to economics, combining an evolutionary perspective and economics by interpreting them innovatively. Robert and Yoguel (2013) reviewed the relationship between complexity and evolutionary economics of innovation in their studies and proposed a taxonomy of five groups of authors in economic evolution as

(1) habits and routines (Nelson, Winter, Dosi, Hodgson), (
(2) Innovation Systems (Nelson, Freeman, Boschma, Antonelli),
(3) Cumulative Causation (Dosi, Pavitt, Soete, Saviotti);
(4) Self-organization and self-transformation (Metcalfe, Foster, Dopfer, Potts);
(5) Feedback and Increasing Returns.

Based on their findings, they identified two pathways of complexity in economics history. The first path focused on issues such as self-organization and self-transformation and the second described by relying on concepts of feedback and divergence. Foster (2005) maintained complex adaptive systems approach in economics and explained its application explicitly in his paper. After explaining the evolutionary perspective and the relationship between complexity and economics, economic emergence should be a focus for us. Moreover, Frederiksen and Jagtfelt (2013) contributed by explaining key tenets of evolutionary economics with three generalized and conjectural premises as; (1) technological trajectories were defined by internal capabilities with external selection; (2) evolutionary process was based on the premise of self-transformation and entities demonstrated adaptation; (3) long-term evolutionary economic process is path dependent.

Foster and Metcalfe (2012) asserted that entrepreneurship could be accepted as a catalyst for emergence, and tracking creativity, which couldn't succeed in isolation, might lead economic emergence. Moreover, they emphasized that emergence occurred in an economic process starting with novelty generation and ending with competitive selection. Hence, they added that economic order and emergence are inseparable and this was called a 'continuity hypothesis' where economic evolution could not be viewed as analogous to biological evolution, due to its socioeconomic characteristics. In evolutionary economics, economic agents interacted and formed radically new bundles of rules, which could be called 'genuine novelty', and could take the form of capital goods, productive networks, contracting systems and human skills. They proposed that enacting these bundles of rules would involve a process of 'self-organization' and 'unpredictability' with regard to patterns of structure that ultimately form. It can be foreseen that such unpredictability was diminished by a process of 'competitive selection' with domination of new technological, organizational, or institutional rules. This cyclic view changed and evolved the current system consistently and created an evolution in economic systems??.

Unpredictability rule was partially rejected by Antonelli and Ferraris (2017) and they asserted that although innovations were accepted as uncertain, and for this reason in most evolutionary-economic models treated as stochastic, it would be incorrect to consider the process of innovation as totally random awk??. They emphasized that innovations might be expected to occur in a systemic manner by tracking the cumulation of relevant technical advances.

In the evolutionary economics literature, I note two economic emergence studies. Harper and Endres (2012) studied the anatomy of emergence in economics by defining emergence as the outcome of self-organizing, bottom-up growth in agent-based models of complexity. Their perspective may be understood as a complexity-based approach. Based on their findings, evolutionary-institutional economics saw genuine novelty as the single most important hallmark of economic emergence. Such emergence was conceptualized by Frederiksen and Jagtfelt (2013) with Schumpeter's notions of adaptive and creative response. Moreover, emergent patterns and institutions may also exert downward causal effects at the micro-level through changing individuals' habits, purposes and preferences (Hodgson, 2002). For economic patterns, Harper and Endres (2012) suggested four core characteristics to describe emergent properties. These are:

a. *Material Realization:* emergent patterns are realized in physical structures and processes;
b. *Coherence:* the pattern is not a mere aggregate but a systemic whole ("a network") whose components are connected and interact;
c. *Non-distributivity of systemic properties:* the entire pattern possesses at least one systemic (i.e. global) property that none of its components has;
d. *Structure-dependence of systemic properties:* systemic properties of the pattern depend upon the composition of the system (the set of its elements) and its connective structure (the organization of its elements).

They stated that these four core features were common to all forms of emergence in economics. Besides these core features, they proposed the following additional ones:

a. *Genuine Novelty:* the pattern is a genuinely novel structure that is qualitatively different from the patterns from which it emerges;
b. *Unpredictability in principle:* the first-time appearance of a new type of economic pattern cannot be predicted through a rational procedure;
c. *Irreducibility:* the systemic properties of the pattern do not follow from the properties of the system components in isolation or in simpler systems.

After proposing aspects of economic emergence and analyzing emergence structures for capital goods, Harper and Endres (2012) concluded that emergence occurred every time if there was an appearance of a qualitatively new good, technology, design, routine, organizational capability, firm, network, market, or industry. However, it was emphasized that the emergence may have synchronic and diachronic aspects (Harper & Endres, 2012). This means that emergent patterns may demonstrate irreducible features, novel and unpredictable properties by having a certain kind of casual history.

The second study of special note on economic emergence was Martin and Sunley (2012)'s; they put forward four key concepts considering a philosophy of science perspective:

a. *Supervenience:* Higher-level phenomena, patterns and properties emerge from the organization and interactions of lower-level component parts, but are not simply the aggregations of those lower-level components and properties;

b. *Irreducibility:* A systemic (higher level) property or phenomenon is said to emergent if it is irreducible, that is it cannot be reductively explained in terms of the properties of the system's lower level constituent component parts;

c. *Self-organization:* the spontaneous (non-planned or non-imposed) emergence and dynamic self-production of spatio-temporal patterns, structures or functions in systems arising from the actions and interactions of their lower-level components or elements.

d. *Downward causation:* the idea that higher level emergent property, pattern or phenomenon causes, determines, regulates or influences lower level properties and parts, either in those component entities or in their interactions.

With these aspects Martin and Sunley (2012) proposed that economic emergence may create two different outcomes -- destroying an existing trend or adapting it to new conditions. This may be interpreted as radical or incremental innovation.

Finally, for answering the first research question, the aspects of the emergence summarized in Table 1.

Aspects of Emergence	Source
Philosophy of Science Perspective	
a. Emergence is a relation between two sets emergent and emergence basis, b. Has empirical or formal relation within the natural world, c. Emergent is dependent or autonomous from its emergence basis, d. Emergence is ontologically determined by its emergence basis and the emergent is qualitatively novel with regard to its emergence basis, e. Emergence is an empirical relation between an emergent and its emergence basis, ontologically determined and untraceable.	(Sartenaer, 2015)
a. Unpredictability, b. Irreducibility.	(Pepper, 1926)
a. Downward causation, b. Inductively predictable, c. Not reductively explainable, d. Not resultant.	(J. Kim, 1999)
a. Non-additive, b. Novel, c. Non-predictable, d. Non-deducible.	(Stephan, 1992)
Complexity Theory Perspective	
a. Something new appears, newness[2], b. Unpredictability, c. Self-similarity	(Crutchfield, 2013)
a. Radical Novelty, b. Coherence/Collective/Wholeness,	(Goldstein, 2004; Jeffrey Goldstein, 2013)

[2] For Crutchfield (2013) newness was in the eye of an observer. However, he ranged the newness or novelty (he was used these terms interchangeably) from 'obvious' to 'purposeful'. Therefore, it can be asserted that observer dependency make the novelty detection been as a qualitative process. From a different perspective newness described as an index of sociocultural significance and transformative power (Sterne, 2003).

c. A global or macro level, d. Being the product of a dynamical process, e. Being ostensive (downward causation), f. Self-transcending constructions[3].	
a. Subset of the 'vast', b. Continuity c. Unlike kind or Qualitatively Novel, d. Unique synergistic effects that are generated by functional complementarities, or a combination of labor.	(Corning, 2002, 2012)
a. Presence in a macro-state and not in microstate, b. Nonlinearity, c. Demonstrating Weak Emergence Properties, d. Novelty, e. Emergence as a process	(Ryan, 2007)
Evolutionary Economics Perspective	
a. Material Realization, b. Coherence, c. Non-distributivity of systemic properties, d. Structure-dependence of systemic properties e. Genuine Novelty, f. Unpredictability in principle, g. Irreducibility.	(Harper & Endres, 2012)
a. Supervenience,[4] b. Irreducibility, c. Self-organization, d. Downward causation.[5]	(Martin & Sunley, 2012)

Table 1 Summary of Emergence Characteristics

From this review it can be stated that emergence may not apply in scientometrics with its theoretical form as discussed in philosophy of science. At first, it should be admitted that the unpredictability aspect of emergence constrains its use in future studies. However, even it is not expected to describe without its emergence, it is possible to track it after emerged in its earliest period when nature of knowledge considered as cumulative in time and at this time, it is important to find focused time periods regarding scientific and technical/technological change. AWK?? It is clear that researchers in emergence tracking face unknown unknown objects/subjects, but need to determine where to look for possible emergents that may occur.

REVIEW OF SCIENTIFIC AND TECHNOLOGICAL CHANGE AND MICRO-MESO-MACRO LEVELS IN RESEARCH

[3] Goldstein (2004) referred Self-transcending constructions as the dual nature of emergents which were followed from, derived from, or continuous from substrate from which they emerge, also at the same time transcending the forms, dynamic, functionings, laws, and principles operating at the lower substrate level.

[4] Supervenience can be understood as an entity cannot change at a higher level without also changing at a lower level (Sawyer, 2004).

[5] Beyond these characteristics Harper and Endres (2012) put forward three orders of emergence as first order emergence, second order emergence (morphodynamic), third order emergence (developmental or evolutionary).

Science and technology proceed in an evolutionary fashion with theories, tools and applications. Science philosophers study this evolutionary change with different philosophical perspectives. One of the best known theories of scientific change is Thomas Kuhn's scientific revolutions (Kuhn, 1962). Kuhn considered scientific progress as occurring through a series of revolutions. In these revolutions paradigms are continuously replaced by the new ones. Kuhn uses paradigm as a broad concept covering all rules, methods, and consensus knowledge a group of scientists agree upon, which is enough to employ regularly within a discipline. According to Kuhn's structure of scientific revolutions, science advances in an iterative and cyclic process, which consists of several stages: (i) pre-paradigmatic phase, (ii) normal science, (iii) crises, and (iv) revolutions. Current paradigm dominated the research in field is considered to be at the normal science stage. According to Paker (2017), Kuhn distinguished normal science from revolutions and thought that scientists work to develop and deepen the paradigm by putting forward definitions and answering the outstanding questions. Usage of tools and solving the problems by utilizing the current paradigm helps scientists feel comfortable during this period. However, anomalies are recognized and became inevitable and they challenge the foundation of the current paradigm at the crisis stage. In this stage, disagreements are revealed and questions arise on the current paradigm. At the revolutionary stage, compelling evidence is accumulated and competing paradigms become mature enough to take over the existing paradigm that has been evidently incapable of handling the pressing crises. As a result, a new paradigm replaces the existing one and provides an overarching framework for the research community. This process repeats itself as the new paradigm becomes the norm. From now on scientists take this new norm as normal science. Kuhn had several criticisms with relativism and incommensurability in the reviewed literature. Kuhn (1962) gave answers in his book for defending his hypothesis. Although some criticisms remain unaddressed, his ideas should not be expected to measure revolutions, disruptions or emergence with positivist manner because of their recognized nature of ambiguity and complexity. Beyond these criticisms, it can be asserted that emergence may be expected in crisis stage with an unexpected timing.

Furthermore, in their study, Ankeny and Leonelli (2016) proposed a post-Kuhnian perspective on scientific change called "Repertoires". They focused on collaboration intensity with an assertion that their approach permitted to investigate the interrelation between various components of scientific practice. With this perspective, they assumed that the concept would provide a framework that could facilitate a more comprehensive view of the drivers of scientific change (Ankeny & Leonelli, 2016). It is thought that a science mapping perspective is compatible with the collaboration focus of the authors for understanding scientific change. This study may be interpreted as increasing collaboration intensity may give clues about possible emergent outcomes??.

Fuchs (1993) challenges the Kuhnian paradigm shift model as an oversimplified view of a complex reality. Therefore, Fuchs (1993) proposed that task uncertainty and mutual dependence are the two variables which derive four types of scientific change when they interact. Task uncertainty refers to the level of uncertainty involved in the course of scientific inquiry. The task uncertainty is high in scientific frontiers where research is essentially exploratory in nature and there is a high amount of tacit knowledge involved. In contrast, task uncertainty is low in areas where tasks are routinized. Mutual dependence refers to the social and organizational dependencies between scientists and their competing peers. A combination of high task uncertainty and high mutual dependence will lead to original scientific discoveries. A combination of low task uncertainty and high mutual dependence will result in specialization to maintain the tension between scientists with high mutual dependence while they work on routinized research. In this perspective, it can be proposed that the more competitive the scientific environment, the more possible to expect technical or technological emergence in this stage.

Another theory of the evolution of a scientific discipline is proposed by Shneider (2009). Based on his proposal, the evolution of a scientific discipline is divided into four stages as (1) conceptualization stage; (2) tool and instrument development stage; (3) investigation of the research questions supported by the newly developed enabling techniques stage; and (4) transferring tacit knowledge to codified and routinized knowledge stage. It can be asserted that emergence may be seen in the fourth stage while creating and codifying the knowledge.

After reviewing scientific change perspectives in these literatures, technological/technical change can be understood by evolutionary economists with cyclic perspectives. Models of technology evolution may take this as incremental innovation punctuated by periods of radical innovations that spur the emergence of new technologies (Cattani, 2006). Dosi (1997) discussed a cyclic perspective with path-dependence characteristics and proposed that an evolutionary view might approach this issue with a process understanding. In these cyclic perspectives, the concept of technology is used differently in the literature discussed by Taylor and Taylor (2012). They found that distinguishing technology from product was not possible in definitions and in their reviewed definitions 'technic' was included in all of them.

According to B. Kim (2003), technology life cycle is related to the concept of technology paradigms. These paradigms designate technology platforms for successive generations of technology. From a network perspective, Suarez (2004) stated that no technology works in isolation. At each level development needs to coordinate and be compatible with other systems or products, and this aspect makes it more complex, with increasing non-linearly related actors. External network relationships are discussed by Cattani (2006). He introduces a technological speciation concept and he asserted that technological speciation would occur when selection forces in a new domain were significantly different from those faced in the other domains. Cattani (2006)'s proposition in this concept might be cast as an adaptation perspective and he discussed that novelty may be generated by selection acting upon existing variation but not explain how this variation was created in the first place.

A seminal work in technological change was Anderson and Tushman (1990)'s in which they applied an evolutionary perspective. They proposed a cyclical model and put emphasis on emergence of dominant designs which were classified as competence-destroying and competence-enhancing technological discontinuities. They asserted that technological discontinuities would occur continuously with two phases called era of ferment and era of incremental change. Dominant design discriminated these two phases with its emergence. By applying cases and testing their hypothesis, they found that the competitive environment changed in repeated patterns over time and this change was linked to systematic environmental change. From this cyclical model it can be asserted that even if it is not possible to identify and forecast technological emergence before, it may be possible to track its development in the subsequent era of incremental change.

Another technology life cycle model is Abernathy and Utterback (1978)'s. This model was designed with three phases -- fluid phase, transitional phase, and specific phases. Based on Roberts and Liu (2001), Utterback added a discontinuities phase later as a fourth dimension. Roberts and Liu (2001) asserted that emergence of a dominant design was expected to start a transitional phase. Therefore for searching and predicting technological/technical emergence, it may be useful to understand the weak signals of the fluid phase's end and antecedents of a dominant design. Because the proposed model is based on product life cycle, considering market dynamics, it can be proposed to utilize patent data and economic statistics for technological trend detection and prediction. While using patent data, some shortcomings stated by Jarvenpaa, Makinen, and Seppanen (2011) for measuring innovation or technological progression and proposed solution for overcoming these obstacles should be kept in mind [??what shortcomings?].

C. Lee, Kim, Kwon, and Woo (2016) proposed a stochastic model using a Hidden Markov Model to detect technology stages. They emphasized the importance of a multi-indicator use perspective to reflect technology progression properly and the combination of different databases for data accuracy. They applied seven patent indicators -- patent activity; technology developers; technology scope; prior knowledge; technology value; duration of examination; and protection coverage -- in their model. They claimed to contribute to existing research by demonstrating idiosyncratic and intangible aspects of a technology's progression.

Jarvenpaa et al. (2011) reviewed the theoretical background of technology life cycle indicators and, citing Watts and Porter (1997)'s study, demonstrated these indicators as in Table 1.

Factor	Indicator
R&D Profile	
Fundamental Research	No. of items in databases such as Science Citation Index
Applied Research	No. of items in databases such as Engineering Index
Development	No. of items in databases such as US Patents
Application	No. of items in databases such as Newspapers Abstracts Daily
Societal Impacts	Issues raised in the Business and Popular Press Abstracts
Growth Rate	Trends over time in number of items
Technological Issues	Technological needs noted
Maturation	Types of topic receiving attention
Offshoots	Spin-off technologies linked

Table 1 Technology life cycle indicators (Watts & Porter, 1997)

The indicators demonstrated in Table 1 might be classified based on their predictive and descriptive powers. Even most of the cyclical models were linear??, a systemic perspective should be applied while using these indicators. Jarvenpaa et al. (2011) described the systemic necessity as death of linearity assumption and emphasized the trend in systemic, interactive and complexity perspectives in literature??. Moreover, in application, they applied different databases for describing different innovation phases as; (1) Science Citation Index for Fundamental Research; (2) Compendex for Applied Research; (3) US utility patents for Development; (4) LexisNexis: All English Language News for Application. By the way, it can be concluded that different databases demonstrate different technology stages and it can be assumed that not all databases may suit for technological emergence research.

B. Kim (2003) took uncertainty in Technology life cycle context as 'unpredictability' in terms of performance, utility, and economics associated with utilizing the technology. Then, he asserted that consumers adopt a technology with low uncertainty much faster than that with high uncertainty. A less uncertain technology life cycle would reach its natural maturity earlier than did a more uncertain technology life cycle. With this description, it can be said that uncertainty or unpredictability depends on its inherent characteristics. Beyond B. Kim (2003)'s unpredictability proposition, Cattani (2006) introduced a pre-adaptation concept and asserted that in the course of technology evolution one could identify the existence of ideal cut-off point in which firms accumulated knowledge without forecasting its subsequent applications and the phase in which firms leveraged that knowledge in a new domain as new environmental conditions and information possible uses came along.

When distributions are considered, it can be seen that technology progression has been mostly tracked by using the general form of an S-curve which is thought to reach saturation at maturity. Taylor and Taylor (2012) asserted that at this point a new disruptive technology may emerge to replace the old one and the cycle begin again. Technological progression might be interrupted with the replacement technology which demonstrated higher performance than the old one. From these aspects, it can be asserted that incremental innovations make S-curve continuous with substitutions and radical innovations have their own S-curves [??note envelope curves here]. Tech emergence research may have two objectives. The first one is tracking and predicting substitutive technologies and the second one is searching weak signals of radically innovative technologies. This substitutive perspective was prepared by Fisher and Pry (1971) and tested in tracking three different technological change cases. Therefore, it can be concluded that before tracking technological emergence goodness-of-fit to Fisher-Pry model may be searched??.

One last question to answer is what are significant levels of technological emergence? When the level of studies is taken into consideration, many studies describe and analyze the relationship between different levels in social science research. Here, we put forward a hierarchical classification of technological/technical emergence by considering creativity and publication processes. This proposed hierarchical classification is demonstrated in Figure 2.

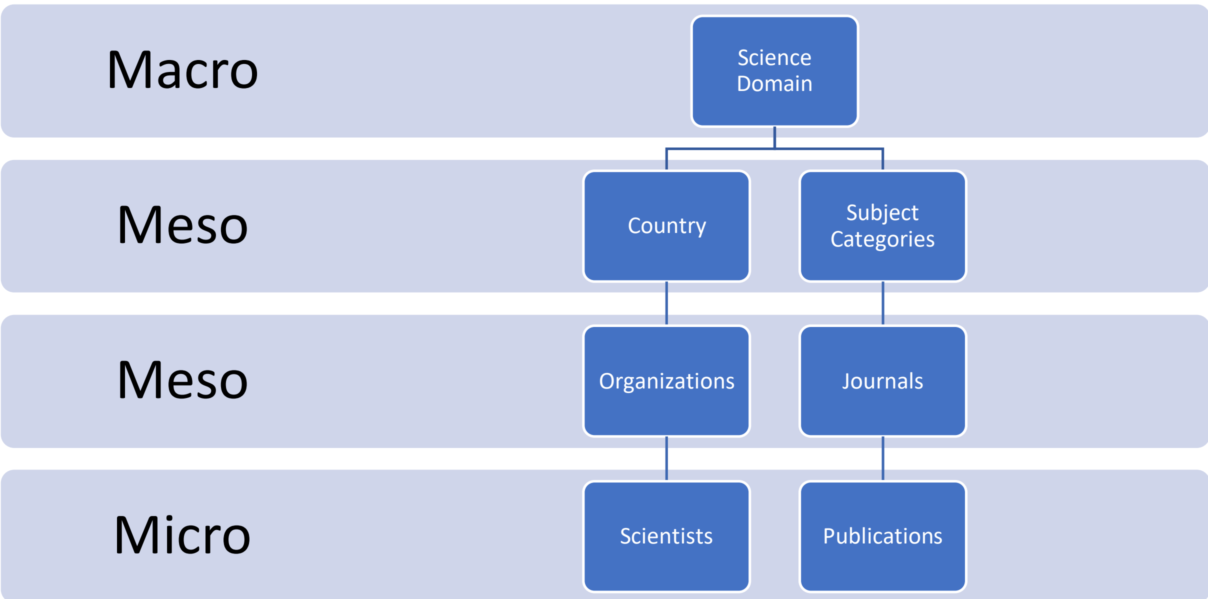

Figure 2.

As can be seen in Figure 2, there are two different, but related, streams in publication research. One of them is inspired by a creativity perspective and the other one offers a scientific publication process perspective. Based on this, scientists are in the micro-level. However, it is clear that scientists are not isolated beings, but rather a specialized component of a creation system in which knowledge accumulates. Each scientist interacts with a subset of other scientists, in direct and indirect ways. The scientist has her internal and external structure: internal structure is built upon cognitive and imaginative capabilities and external structure is built from specific interactions with other scientists or accumulated knowledge in the system. This aspect makes micro studies more complex. On the other side, there are publications. In these scientific works, scientists collaborate and create new ideas with a combined perspective. Therefore, it may be hard to decompose intellectual capital of publications to individual scientists. So, without weighting the participation of scientists to the idea how can it be distinguished? Publications interact via citations. In this sense, co-citation, direct citation and bibliographic coupling methods have been used to measure these networks.

Aggregation of micro level creates meso level studies. In the meso level, institutional, organizational, or categorical outcomes may be considered. When a creativity perspective is analyzed, it can be asserted that organizational and country levels may be accepted as meso levels. By doing research in this level, organizational and country-level aspects of emergence may be realized. On the other side, journals and subject categories may be seen.

Macro level is described with science domains. Creation process and publication process are combined at the top, as if they were complementary. They all should be accepted as actors of the macro network. Because there is a problem in combining different actors to deduce macro outcomes in the literature, it is thought to describe them for avoiding hierarchical mismatching for future studies??.

CONCEPTUAL MODEL OF EMERGENCE

Various explanations of emergence in philosophy, complexity and evolutionary economics, make it more complicated to interpret. However, it should be noted that the context may enhance the understanding of emergence. Scientific change and technological change were explained in literature with a cyclical and path-dependent aspects. In these perspectives the main question is how to find emergence. This likens to "unknown unknowns" in management decision making literature. An unknown-unknown is one that the decision maker does not imagine and therefore does not consider, because it has not emerged yet. However, according to Feduzi and Runde (2014), even emergence and epistemic constraints limit imagining unknown-unknowns by decision makers, unknown-unknowns could be divided to two with knowable-unknowns and unknowable-unknowns theoretically??. Technological emergence can be treated as knowable-unknowns, which can be defined as unknown unknowns that could have been transformed into known unknowns at some point in time in the absence of epistemic constraints, in this study because of its cyclic and path-dependent characteristics.

From this point of view, even though definitions differ, it can be asserted that an evolutionary perspective remains. Hence, an evolutionary perspective and its aspects should be applied to technological emergence with a new interpretation, because even though the analogy is coming from biology, human decisions and motives (Penrose, 1952) may demonstrate weak signals on the predictability of innovation and firm development. From this proposition, it can be asserted that technological emergence can be accepted as path dependent with technological frames (Kaplan & Tripsas, 2008). Based on a technological frame approach of Orlikowski and Gash (1994), actors' technological frames did not spring up randomly, but rather were the encoding of their prior history. Therefore, it can be asserted that emergence search in a technological context can be applied to understand the knowledge accumulation of actors in historical time series. [so, how do evolutionary and technological perspectives correspond??]

A reductionist and individualist approach suggests that macro system properties may be tracked by tracking components and parts. In this sense, knowledge and its accumulative nature may rationalize this mechanistic perspective, which was criticized by Sawyer (2004), citing Bunge and Hedström and Swedberg as mechanistic explanations that couldn't predict, but only explain. However, by considering qualitative and quantitative models together we might overcome this criticism with incomplete determinism (Hofkirchner, 1998) and partly reject the pure mechanistic perspective. Moreover, it should be kept in mind that, publications are collaboratively created materials and this collective phenomenon may not be reduced to individual level analysis as mentioned in our review of different levels in social science research.

This study interprets the path-dependent structure from an evolutionary perspective. With this it can be asserted that emergence should be understood in scientific and technological change by using trends, needing some critical aspects to be demonstrated. These are:

1. Qualitative Novelty;
2. Continuation;
3. Synergistic effect;
4. Irregularity;
5. Creating Entropy; (Higher degree of complexity exhibit novel properties (J. Kim, 1999))
6. Demonstrating Unexpectedness;

When these aspects are evaluated, it can be asserted that qualitative and quantitative models should be combined to find a reliable measurement system for Technological Emergence.

In addition, Li, Porter, and Suominen (2017) also addressed distinctions between "emerging technologies" and "disruptive technology" concepts. They tried to explain the relationship between disruptive innovation/technology and emerging technology fields by applying co-citation and bibliographic coupling networks. Finally, they saw that presence of emergence was dominant by volume of articles and the concept of disruptiveness relatively was discovered late-coming??. Moreover, they noted a lack of theoretical orientation in research regarding technological emergence.

DISCUSSION AND CONCLUSION

References

Abernathy, W. J., & Utterback, J. M. (1978). Patterns of industrial innovation. *Technology Review, 80*(7), 40-47.

Alexander, J., Chase, J., Newman, N., Porter, A., & Roessner, J. D. (2012). Emergence as a conceptual framework for understanding scientific and technological progress. *Picmet '12: Proceedings - Technology Management for Emerging Technologies*, 1286-1292.

Anderson, P., & Tushman, M. L. (1990). Technological discontinuities and dominant designs - a cyclical model of technological-change. *Administrative Science Quarterly, 35*(4), 604-633. doi:Doi 10.2307/2393511

Anderson, P. W. (1972). More is different. *Science, 177*(4047), 393.

Ankeny, R. A., & Leonelli, S. (2016). Repertoires: A post-kuhnian perspective on scientific change and collaborative research. *Studies in History and Philosophy of Science, 60*, 18-28. doi:10.1016/j.shpsa.2016.08.003

Antonelli, C., & Ferraris, G. (2017). The marshallian and schumpeterian microfoundations of evolutionary complexity: An agent based simulation model. In *Foundations of economic change: A schumpeterian view on behaviour, interaction and aggregate outcomes* (pp. 461-500). Cham: Springer International Publishing.

Boulding, K. E. (1991). What is evolutionary economics? *Journal of Evolutionary Economics, 1*(1), 9-17. doi:10.1007/BF01202334

Carley, S. F., Newman, N. C., Porter, A. L., & Garner, J. G. (2017). A measure of staying power: Is the persistence of emergent concepts more significantly influenced by technical domain or scale? *Scientometrics, 111*(3), 2077-2087. doi:10.1007/s11192-017-2342-x

Cattani, G. (2006). Technological pre-adaptation, speciation, and emergence of new technologies: How corning invented and developed fiber optics. *Industrial and Corporate Change, 15*(2), 285-318. doi:10.1093/icc/dtj016

Chen, C. M. (2006). Citespace ii: Detecting and visualizing emerging trends and transient patterns in scientific literature. *Journal of the American Society for Information Science and Technology, 57*(3), 359-377. doi:10.1002/asi.20317

Corning, P. A. (2002). The re-emergence of "emergence": A venerable concept in search of a theory. *Complexity, 7*(6), 18-30. doi:10.1002/cplx.10043

Corning, P. A. (2012). The re-emergence of emergence, and the causal role of synergy in emergent evolution. *Synthese, 185*(2), 295-317. doi:10.1007/s11229-010-9726-2

Crutchfield, J. P. (2013). 15 is anything ever new? Considering emergence.

Dawid, H. (2006). Chapter 25 agent-based models of innovation and technological change. In *Handbook of computational economics* (Vol. 2, pp. 1235-1272): Elsevier.

Dosi, G. (1997). Opportunities, incentives and the collective patterns of technological change. *Economic Journal, 107*(444), 1530-1547. doi:Doi 10.1111/1468-0297.00239

Feduzi, A., & Runde, J. (2014). Uncovering unknown unknowns: Towards a baconian approach to management decision-making. *Organizational Behavior and Human Decision Processes, 124*(2), 268-283. doi:10.1016/j.obhdp.2014.04.001

Fisher, J. C., & Pry, R. H. (1971). Simple substitution model of technological change. *Technological Forecasting and Social Change, 3*(1), 75-88. doi:Doi 10.1016/S0040-1625(71)80005-7

Foster, J. (2005). From simplistic to complex systems in economics. *Cambridge Journal of Economics, 29*(6), 873-892. doi:10.1093/cje/bei083

Foster, J. (2006). Why is economics not a complex systems science? *Journal of Economic Issues, 40*(4), 1069-1091.

Foster, J., & Metcalfe, J. S. (2012). Economic emergence: An evolutionary economic perspective. *Journal of Economic Behavior & Organization, 82*(2-3), 420-432. doi:10.1016/j.jebo.2011.09.008

Frederiksen, P., & Jagtfelt, T. (2013). Exponential expansion in evolutionary economics: A model proposition. *Journal of Economic Issues, 47*(3), 705-718. doi:10.2753/Jei0021-3624470306

Fuchs, S. (1993). A sociological-theory of scientific change. *Social Forces, 71*(4), 933-953. doi:Doi 10.2307/2580125

Goldspink, C., & Kay, R. (2010). Emergence in organizations: The reflexive turn. *Emergence : Complexity and Organization, 12*(3), 47-63.

Goldstein, J. (2002). The singular nature of emergent levels: Suggestions for a theory of emergence. *Nonlinear Dynamics, Psychology and Social Sciences, 6*(4), 293-309.

Goldstein, J. (2003). Emergence, creativity, and the following and negating. *The Innovation Journal: The Public Sector Innovation Journal, 10*(3), 1-12.

Goldstein, J. (2004). Emergence, creative process, and self-transcending concstructions. In M. Lissack & K. Richardson (Eds.), *Managing organizational complexity philosophy, theory and application* (Vol. Managing the Complex). Greenwich, Conn.: Information Age Pub.

Goldstein, J. (2013). Complexity and philosophy: Re-imagining emergence: Part 1. *Emergence : Complexity and Organization, 15*(2), 78-104A.

Goldstein, J. (2013). Complexity and philosophy: Re-imagining emergence: Part 1. *Emergence: Complexity and Organization, 15*(2), 78-104.

Harper, D. A., & Endres, A. M. (2012). The anatomy of emergence, with a focus upon capital formation. *Journal of Economic Behavior & Organization, 82*(2), 352-367. doi:https://doi.org/10.1016/j.jebo.2011.03.013

Hodgson, G. M. (2002). Darwinism in economics: From analogy to ontology. *Journal of Evolutionary Economics, 12*(3), 259-281. doi:DOI 10.1007/s00191-002-0118-8

Hofkirchner, W. (1998). Emergence and the logic of explanation an argument for the unity of science. *Acta Polytechnica Scandinavica, Mathematics, Computing and Management in Engineering Series, 91*, 23-30.

Jarvenpaa, H. M., Makinen, S. J., & Seppanen, M. (2011). Patent and publishing activity sequence over a technology's life cycle. *Technological Forecasting and Social Change, 78*(2), 283-293. doi:10.1016/j.techfore.2010.06.020

Kaplan, S., & Tripsas, M. (2008). Thinking about technology: Applying a cognitive lens to technical change. *Research Policy, 37*(5), 790-805. doi:10.1016/j.respol.2008.02.002

Kim, B. (2003). Managing the transition of technology life cycle. *Technovation, 23*(5), 371-381. doi:10.1016/S0166-4972(02)00168-2

Kim, J. (1999). Making sense of emergence. *Philosophical Studies, 95*(1), 3.

Kuhn, T. (1962). *The structure of scientific revolutions*. Chicago: University of Chicago Press.

Lee, C., Kim, J., Kwon, O., & Woo, H. G. (2016). Stochastic technology life cycle analysis using multiple patent indicators. *Technological Forecasting and Social Change, 106*, 53-64. doi:10.1016/j.techfore.2016.01.024

Lee, Y. N., Walsh, J. P., & Wang, J. (2015). Creativity in scientific teams: Unpacking novelty and impact. *Research Policy, 44*(3), 684-697. doi:10.1016/j.respol.2014.10.007

Li, M., Porter, A. L., & Suominen, A. (2017). Insights into relationships between disruptive technology/innovation and emerging technology: A bibliometric perspective. *Technological Forecasting and Social Change*. doi:10.1016/j.techfore.2017.09.032

Martin, R., & Sunley, P. (2012). Forms of emergence and the evolution of economic landscapes. *Journal of Economic Behavior & Organization, 82*(2), 338-351. doi:https://doi.org/10.1016/j.jebo.2011.08.005

Morrison, M. (2015). Why is more different? In *Why more is different: Philosophical issues in condensed matter physics and complex systems* (pp. 91-114). Berlin, Heidelberg: Springer Berlin Heidelberg.

Munier, F., & Ronde, P. (2001). The role of knowledge codification in the emergence of consensus under uncertainty: Empirical analysis and policy implications. *Research Policy, 30*(9), 1537-1551. doi:Doi 10.1016/S0048-7333(01)00166-4

Orlikowski, W. J., & Gash, D. C. (1994). Technological frames - making sense of information technology in organizations. *Acm Transactions on Information Systems, 12*(2), 174-207. doi:Doi 10.1145/196734.196745

Paker, M. M. (2017). On the applicability of theories of scientific change to economics. Retrieved from https://static1.squarespace.com/static/560ab115e4b0f2cf50225c2d/t/59df6dd8bebafb49379cfd4b/1507814873548/Paker_TheoriesOfScientificChange%2Cpdf.pdf

Penrose, E. T. C. (1952). Biological analogies in the theory of the firm. *The American Economic Review, 42*(5), 804-819.

Pepper, S. C. (1926). Emergence. *The Journal of Philosophy, 23*(9), 241-245. doi:10.2307/2014779

Robert, V., & Yoguel, G. (2013). The approach of complexity and evolutionary economics of innovation. *Filosofia de la Economia, 1*(1), 187-226.

Roberts, E. B., & Liu, W. Y. K. (2001). Ally or acquire? How technology leaders decide. *Mit Sloan Management Review, 43*(1), 26-+.

Rotolo, D., Hicks, D., & Martin, B. R. (2015). What is an emerging technology? *Research Policy, 44*(10), 1827-1843. doi:10.1016/j.respol.2015.06.006

Ryan, A. J. (2007). Emergence is coupled to scope, not level. *Complexity, 13*(2), 67-77. doi:10.1002/cplx.20203

Sartenaer, O. (2015). Synchronic vs. Diachronic emergence: A reappraisal. *European Journal for Philosophy of Science, 5*(1), 31-54. doi:10.1007/s13194-014-0097-2

Sartenaer, O. (2016). Sixteen years later: Making sense of emergence (again). *Journal for General Philosophy of Science, 47*(1), 79-103. doi:10.1007/s10838-015-9312-x

Sawyer, R. K. (2001). Emergence in sociology: Contemporary philosophy of mind and some implications for sociological theory. *American Journal of Sociology, 107*(3), 551-585. doi:Doi 10.1086/338780

Sawyer, R. K. (2004). The mechanisms of emergence. *Philosophy of the Social Sciences, 34*(2), 260-282. doi:10.1177/0048393103262553

Shneider, A. M. (2009). Four stages of a scientific discipline; four types of scientist. *Trends in Biochemical Sciences, 34*(5), 217-223. doi:10.1016/j.tibs.2009.02.002

Small, H., Boyack, K. W., & Klavans, R. (2014). Identifying emerging topics in science and technology. *Research Policy, 43*(8), 1450-1467. doi:10.1016/j.respol.2014.02.005

Solow, R. M. (1957). Technical change and the aggregate production function. *Review of Economics and Statistics, 39*(3), 312-320. doi:Doi 10.2307/1926047

Stephan, A. (1992). Emergence-a systematic view on its historical facets. *Emergence or reduction*, 25-48.

Sterne, J. (2003). Bourdieu, technique and technology. *Cultural Studies, 17*(3-4), 367-389. doi:10.1080/0950238032000083863

Suarez, F. F. (2004). Battles for technological dominance: An integrative framework. *Research Policy, 33*(2), 271-286. doi:10.1016/j.respol.2003.07.001

Taylor, M., & Taylor, A. (2012). The technology life cycle: Conceptualization and managerial implications. *International Journal of Production Economics, 140*(1), 541-553. doi:10.1016/j.ijpe.2012.07.006

Teran, M. V. (2017). Philosophical explorations for a concept of emerging technologies. *Techné: Research in Philosophy and Technology*. doi:10.5480/techne201792170

Watts, R. J., & Porter, A. L. (1997). Innovation forecasting. *Technological Forecasting and Social Change, 56*(1), 25-47. doi:Doi 10.1016/S0040-1625(97)00050-4

Wierzbicki, A. P. (2015). Systems theory, theory of chaos, emergence. In *Technen: Elements of recent history of information technologies with epistemological conclusions* (pp. 175-188). Cham: Springer International Publishing.