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Analysing the theoretical roots of technology emergence: an evolutionary perspective

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Abstract
There has been much research concerning emergence in technology, ever since knowledge has been accepted as a prime engine of economic growth. However, even though there are a growing number of publications, the concept remains ambiguous. In this study, we aim to trace emergence discussions to find the evolution of related concepts, in order to explore usage in the technological context. To achieve this, the philosophy of science, complexity, and economic literatures are reviewed in accordance with the emergence concept qualitatively. Then, a bibliometrics study is performed to strengthen the qualitative argument and find evidence of emergence in technology studies for comparison. Based on the findings, we can assert that the definition of technology emergence needs to be revised with consideration of its theoretical foundations. Moreover, after discussion, research questions are posed for future research.

Keywords Emergence · Technology emergence · Emerging technology · Evolution · Conceptual evolution

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Introduction

There have been many studies aiming to conceptualize emerging technologies (Alexander et al. 2012; Rotolo et al. 2015; Small et al. 2014) and model (Chen 2006). Moreover, while conceptualizing and modeling technology, many phrases for interpreting technological changes have been used, such as "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, he assessed that the "emerging technologies" concept differs from others because of its understanding from other disciplines (Teran 2017). The concept is also used mostly with its dictionary definition, which may degrade its actual understanding. However, these efforts mostly focused on identifying, tracking, and forecasting "emergence" without mentioning the nature of emergence and its aspects.

Historically, the emergence concept appeared in science because of unexpected changes, especially in biology, chemistry, and physics. "Emergence" was coined at the end of the nineteenth century and became popular in the philosophy of science at the beginning of the twentieth century, reflecting in discussions on the nature of emergence. These discussions have found themselves useful with developments in evolutionary science. Increasing understanding of the concept in philosophy attracted different scientific groups. For instance, these discussions also inspired researchers to examine emergence in complex systems from the 1930s. Complexity theorists also tried to explain different aspects of the emergence concept with self-organizing and synergistic characteristics. In addition to the philosophy of science scholars and complexity theory researchers, economists discussed emergence from the evolutionary economics' perspective from the 1950s. Some economists even asserted that the evolutionary perspective was different from biological sciences, with the emergence concept being interpreted in economics with consideration for philosophical discussions and complexity explanations after the 1940s.

As briefly reviewed, there have been on-going discussions for understanding emergence in literature with three main academic branches. In all these branches, the emergence concept has been interpreted by considering inherent dynamics. Therefore, the aim of this study is to examine the evolution of emergence concepts retrospectively. While tracking quantitatively by using science mapping, we also review the literature qualitatively to understand changes in meanings of emergence. We hope to contribute to existing literatures by interpreting different scientific roots of emergence concepts for scientometricians to inform future research.

In the second section, the theoretical background of emergence is reviewed qualitatively by comparing different perspectives. Then, the search strategy and data retrieval methodology are explained; science maps are exhibited in the third section. In the fourth section, findings are discussed and discrepancies of the emergence concept's usage are emphasized. Finally, in the conclusion, the emergence concept and its possible aspects are summarized in accordance with a technology context.

Theoretical background of emergence concepts

The literature review takes into consideration three theoretical branches (as previously mentioned)—Philosophy of Science, Complexity Theory, and Evolutionary Economics—narrated here one by one.

Philosophy of science perspective

The emergence concept has been discussed in the philosophy of science since the 1800s. Sawyer (2001) dated the emergence concept to 1875 (Goldspink and Kay 2010) and expressed that the term was first coined by George Henry Lewes for distinguishing resultants and emergents. Stephan (1992) divided emergence discussion in the philosophy of science into four periods. The first period was in the nineteenth century, including the works of John Stuart Mill, Alexander Bain, and George Henry Lewes. The second period came in the early twentieth century and concerned the attempt to offer an alternative to mechanisms and vitalism[1] by introducing a third theory called emergentism, with seminal works from Samuel Alexander (Space, Time and Deity, 1920), Lloyd Morgan (Emergent Evolution, 1923), and C.D. Broad (The Mind and Its Place in Nature, 1925). Sawyer (2001) added Whitehad (1926) to the second period and asserted that, with Morgan, they were the pioneers of British emergentism and rejected dualist vitalism,[2] accepting the materialist ontology—though in a non-reductive version of it—that only physical matter existed. The third period was the 1940s, and in this period there were discussions on emergentism with novelty and non-predictability aspects by W.T. Stace (Novelty, Indeterminism, and Emergence, 1939), P. Henle (The Status of Emergence, 1942), and G. Bergmann (Holism, Historicism and Emergence, 1944). 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". In the third part based on Sartenaer (2018), emergence was marginalized and mostly neglected. This is unsurprising, as the dominant view then was reductionism[3] (motivated by subsequent scientific achievements like quantum mechanics, molecular biology, and the rise of neuroscience, among other things). Some emergentist "resistance" existed, of course, but that was not mainstream. The fourth period was defined by Stephan (1992) in the 1970s; he identified this period with discussions of psycho-physical problems of emergence. Sawyer (2001) furthered this timeframe to the 1990s and described studies focusing on core concepts in computational modeling of complex systems, including connectionism, artificial life, and multi-agents of social systems subjects. In this sense, it is assumed that the roots of understanding of the emergence concept began in the 1800s and applying the concept to different fields started

[1] Vitalism is a thought that living organisms are fundamentally different from non-living entities because they contain some non-physical element or are governed by different principles than are inanimate things (Bechtel and Richardson 1998).

[2] Dualism is the view that mental phenomena are, in some respect, nonphysical (Rosenthal 1998).

[3] 'Reduction' is a term of natural language, and, building upon its common metaphoric meaning philosophers use it to designate relations of particular philosophical importance in a number of closely related fields, especially in the philosophy of science, the philosophy of mind, and metaphysics (for more please check https://plato.stanford.edu/entries/scientific-reduction/Accessed at 15.08.2018).

in the 1920s. Therefore, the 1900s may be a good starting point for retrieving data related to emergence discussions.

Beyond its chronological development, it may be asserted that emergentist philosophy understands the term *emergence* differently from technology and innovation scholars. At first emergentist theories make statements about the world distinguishing two aspects: current state (or "being")—the synchronous aspect by considering its historical composition; and its evolution (or "becoming)—the diachronous aspect.

The synchronous aspect can be characterized by the idea that a whole can have genuinely different properties than do its parts. It should be noted that some properties of a whole cannot be explained by deduction from the properties of parts and such properties are called emergent, as opposed to reducible. In this sense, Anderson (1972) emphasized that the whole is not greater than, but very different from the sum of parts, and suggested that emergence has a strong physical dimension.

The diachronous aspect deals with the appearance of new things with new properties over time. In this perspective, qualitative novelty[4] is important. It is thought that these new properties cannot be predicted from even perfect knowledge of the old properties. This aspect would distinguish emergents from resultants.

Emergentists saw the world in a hierarchy, which was structured in higher and lower layers of existence. They also thought that emergent properties anchored in structures and didn't exist independently of them.

Goldspink and Kay (2010) differentiated social systems from other fields with human agents' cognitive aspects and emphasized the theory of autopoiesis, which is described as humans coordinating their actions by way of communication. They proposed an analogy by using holograms for describing the whole, taking into consideration that the removal of every part (agents) may reduce the resolution. Also, this analogy would stress coherence in collaboration networks and pattern formation. Sawyer (2001) emphasized that for all emergentists, interaction is a central issue and asserted that higher-level properties emerge from interaction of individuals in a complex system and the complexity of interactions among components might be another variable contributing to emergence. He also compared individualists and collectivists in his study, and from the collectivists' perspective explained irreducible systems with nonaggregativity,[5] near decomposability,[6] localization, and complexity of interaction characteristics. Sawyer (2001) expressed that most social properties were not aggregative and thus they should be treated as emergent.

[4] Generally one speaks of "qualitative novelty" when new kinds of properties arise out of the interactions of pre-existing properties (e.g. the property of water being liquid arising from the synthesis of oxygen and hydrogen being gaseous), while "quantitative novelty" is usually meant to refer to the coming into being of a new numerical value of a pre-existing property (e.g. the property of water of having a mass of $(x+y)$ grams arising from the synthesis of x grams of oxygen with y grams of hydrogen). For detailed discussion on this distinction and its connection to evolution and emergence, see Blitz (1992).

[5] Based on Sawyer (2001), aggregative properties meet four criteria, and most social properties do not satisfy them. These criteria are; (1) the parts of the system is intersubstitutable, (2) an aggregative property should remain qualitatively similar under addition or removal of a part from the system, (3) The composition function for the property remains invariant under operations of decomposition and re-aggregation of parts, (4) there are no cooperative or inhibitory interactions among the parts and relations between whole and parts are linear. Therefore he asserted that most social properties are not aggregative and thus are emergent.

[6] Decomposable systems are modular, with each component acting primarily according to its own intrinsic principles. Sawyer (2001) asserted that systems that are not nearly decomposable are likely to have emergents system properties.

Complexity theory perspective

Along with theoretical discussions in the philosophy of science, complexity theorists handled the concept by trying to understand it from a complexity approach. Wierzbicki (2015) defines the emergence principle with a complexity perspective as having “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 as qualitatively different and irreducible. Moreover, Corning (2002) proposed that emergence produced “self-organizing” processes and compared definitions of emergence from different disciplines. Based on the answers, he stated that it was hard to decide on a concrete and compromised definition of the emergence concept. He also proposed a definition for the 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”.

From a different perspective in complexity research, Goldstein (2003) connected emergence to creativity processes in his study and proposed a thesis that emergent and creative processes shared a common logic of novelty generation. He exemplified this relationship by demonstrating the use of emergence by scholars, such 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 the creativity process in knowledge management may lead to identifying and tracking emergent properties. Goldstein claimed that radically novel outcomes might be reached after improvising or negating past patterns. Thus, it can be thought that a paternalistic approach may identify radical novelty. However, the qualitative nature of novelty may again be problematic and needs expert[7] judgment. During the judgment process, expert opinions should be focused on newness, originality, and changing the potential of pre-existing patterns.

Like the creativity analogy, Crutchfield (2013) proposed a discovery process analogy and explained emergence as a process that leads to the appearance of structures 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 his discussion, he proposed two new features—unpredictability and self-similarity—and also emphasized the role of newness from the eye of the observer. With newness, novelty was also mentioned in his study and he had novelty ranging from “obvious’ to “purposeful”. Crutchfield (2013) questioned this newness problem in emergence because he posited that it was always referred to outside the system by some observer that anticipated the structures via a fixed palette of possible regularities. Finally, he summarized his findings with three notions of emergence as (1) the intuitive definition of emergence: “something new appears”; (2) pattern formation: an observer identifies “organization” in a dynamical system; and (3) Intrinsic emergence: the system itself capitalizes on patterns that appear.

[7] The 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 that guided his behavior and his choice between various possible orientations for a given subject.

Evolutionary economics perspective

Evolutionary Economics also considers emergence concepts. An evolutionary concept was associated with economics through Schumpeter's ideas on the importance of innovation in economic growth and creative entrepreneurship at its core. Foster and Metcalfe (2012) asserted that entrepreneurship would be accepted as a catalyst for emergence and tracking creativity, which couldn't succeed in isolation and might lead to economic emergence. Moreover, they emphasized that emergence occurred in an economic process starting with novelty generation and ending with competitive selection. Thus, they added that economic order and emergence are inseparable and this was called a "continuity hypothesis" where economic evolution, with its socioeconomic characteristics, could not be viewed as analogous to biological evolution. In evolutionary economics, the economic agents interact and form radical new bundles of rules, that 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 new technological, organizational, or institutional rules. This view perceives change as ongoing, continually evolving the current system and created evolution in the economic system.

In evolutionary economics literature, we particularly note two economic emergence studies. The first is Harper and Endres (2012) study of 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, which was identified and conceptualized by Frederiksen and Jagtfelt (2013), together 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). Harper and Endres (2012) concluded that emergence occurred every time there was an appearance of a qualitatively new and 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 and Endres 2012). This means that emergent patterns may demonstrate irreducible features, and novel and unpredictable properties by having a certain kind of causal history.

The second study of special note on economic emergence was carried out by Martin and Sunley (2012). They put forward four key concepts, considering philosophy with respect to the science perspective as follows:

(a) *Supervenience*: A set of properties *A* supervenes upon another set *B* just in case no two things can differ with respect to *A*-properties without also differing with respect to their *B*-properties;
(b) *Irreducibility*: A systemic (higher level) property or phenomenon is said to be emergent if it is irreducible; that is, it cannot be reductively explained in terms of the properties of the system's lower level constituent 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 properties, patterns, or phenomena cause, determine, regulate, or influence 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 existing trends or adapting a trend to new conditions. It may thus be interpreted as radical or incremental innovation.

Finally, it can be asserted that the theoretical background of the emergence concept inspired many scholars in different fields with different understandings. It is clear that philosophical understanding of emergence proposes unpredictable, irreducible, and qualitatively novel properties for emergence. Similarly, complexity theorists handle the emergence concept with a systems perspective and assert almost the same properties, addressing emergence as a process. The complexity approach seems more practical when compared with philosophical discussions. Moreover, we have found two focused papers in economics and one of them reflects a philosophy of science perspective and the other one utilizes a complexity approach. The unpredictability argument remains in these studies, but when we consider this argument, it may be ignored because of the nature of knowledge production with its accumulation aspect. In the knowledge society, it can be asserted that tracing knowledge may give weak signals about future outcomes. In the next section, the evolution of the emergence concept is visualized to track its diffusion and convergence.

Methodology

After reviewing the literature, scientometrics have been applied to offer a broad perspective on emergence. Research is prepared in two stages. *The first stage* seeks to understand the conceptual diffusion of emergence concepts. In this stage, four seminal works mentioned in the literature are used for finding diffusion patterns. The literature review suggests that the emergence discussion grew in the 1900s. However, as mentioned, it can also be emphasized that the application of the idea and discussion of the concept advanced notably with cases starting in the mid-1920s, with Alexander (1920), Broad (1925) and Morgan's (1923). Moreover, the complexity theory perspective is thought to have started with the seminal work from Goldstein (1999). In evolutionary economics, the emergence subject is most notably addressed in two studies that are quite recent, so were not added to the search strategy. Therefore, four seminal works (Samuel Alexander, C.D. Broad, Lloyd Morgan, Jeffrey Goldstein) were searched individually in the Web of Science (WoS) to extract publications that participated in the emergence discussions by citing any of these four references. After downloading these citing records, these individual datasets are combined and duplications are removed by using VantagePoint software [www.theVantagePoint.com]. Because the aim of this study is to understand diffusion of the emergence concept, force-directed graphing was applied to WoS categories to see usage of emergence concepts in different fields. After generally understanding the diffusion of the emergence concept, author keywords are clustered by using Principal Components Analysis to visualize and examine the publications in detail.

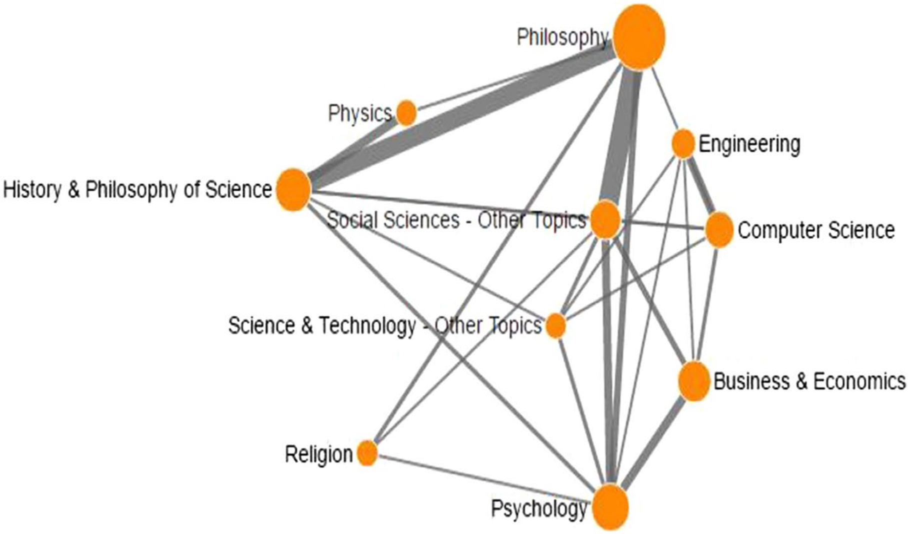

Fig. 1 Co-occurrence network for emergence discussions (records ≥ 20)

In the second stage, we examine the use of emergence in strategy/policy research in a science and technology context. With expert opinions, a journal list is gathered and these journals are searched in the WoS database by considering emerging/emergence in publication titles. The search string is presented in the "Appendix".

After searching and retrieving the dataset, VantagePoint's Natural Language Processing (NLP) routine is applied to the abstract and title fields to examine the use of emergence concepts by authors in the retrieved publication records. Then, full-text search is performed on the selected publications to find conceptual definitions for technology emergence.

Analyses: science mapping of "emergence"

In the first stage, after searching seminal works individually, the publications that cited these were downloaded from WoS and merged in one file using VantagePoint. The duplications were cleaned and finally 816 publications ranging from 1923 to 2018 were ready for analyses; 62% of these publications were journal articles.[8] The nodes of the network (records ≥ 20), which covered 287 records, were extracted as demonstrated in Fig. 1.

As can be seen in Fig. 1, the findings support our qualitative review and assessment on branches of philosophy, complexity, and economics. In Fig. 1, line thickness reflects the degree of co-occurrence between categories. Moreover, it can also be seen in Fig. 1 that the emergence concept is also discussed in the psychology domain, considering 'mind'

[8] Yang and Meho (2006) compared Google Scholar, Scopus, and Web of Science based on their citation analysis performance in their study. Based on their findings Web of Science coverage goes back to 1945 for Science Citation Index, 1956 for Social Science Citation Index, and 1975 for Arts & Humanities Citation Index. Therefore, 1923 to 1956 period may not be covered in Web of Science effectively and it may be accepted as a limitation for our study.

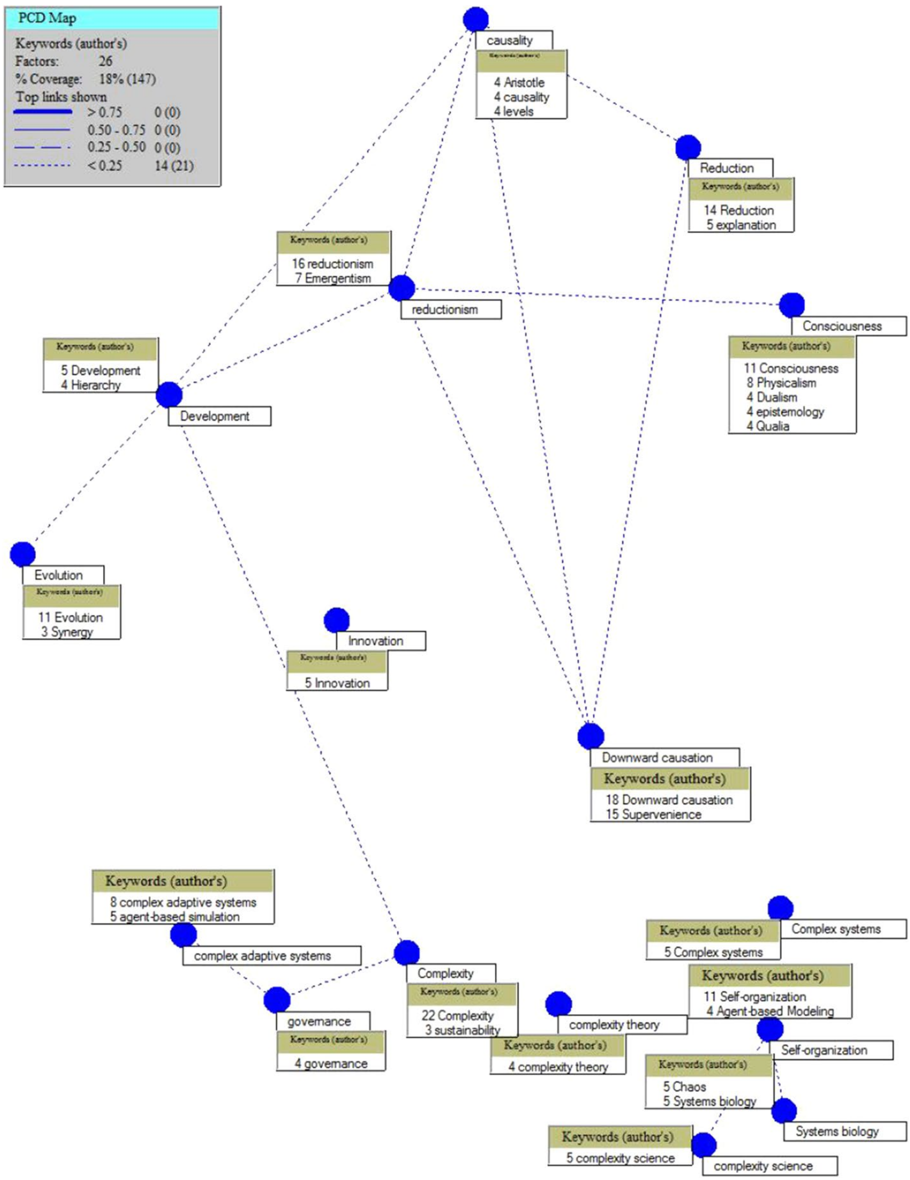

Fig. 2 PCA-based factor analysis of author keywords

discussions. The concept has been discussed mostly by the (history and) philosophy of science domain and in philosophy. In psychology, mind and consciousness discussions had taken place, and human evolution and progress were scrutinized in the studies. The psychology perspective might also be accepted as significant for understanding creativity processes more deeply. In business and economics, computer science, and engineering fields, studies were mostly discussing complexity principles with different subheadings, such as nonlinear programming, self-organization, entropy in systems/organizations/networks, and

Table 1 Selected phrases for analysis

Rank	Abstract (NLP) (phrases) + title (NLP) phrases	# Records
1	Emerging technology	97
2	Emergent science	10
3	Emerging science	6
4	Emerging technology fields	6
5	Managing Emerging Technologies	4
6	Emerging research domain	3
7	Emerging research field	3
8	Emerging research fields	3
9	Emerging research fronts	3
10	Forecasting emerging technologies	3
11	Emerging research	2
12	Emerging scientific fields	2
13	Emerging technologies-based industry	2
14	Emerging technology development	2
15	Emerging TIS	2
16	Select emerging technologies	2
17	Technical emergence	2
18	Tracking emerging technologies	2
19	Emergence via text analyses	1
20	GPT emergence	1
21	Technocultural emergence	1
22	Technological (and commercial) emergence	1
23	Topic's emergence	1

agent-based modeling. From these findings, it can be assumed that emergence discussions were appearing in complexity theory with more application focus on networks/organizations/systems than philosophical discussions considering a system dynamics approach. Furthermore, emergence discussion extends to other research areas by using the same logic with different and domain-specific interpretations. Because of this finding, it is crucial to interpret the emergence concept in science and technology contexts to utilize theoretical foundations of emergence in order to extend its aspects. To help understand associations among emergence-related concepts, author keywords were factored using Principal Components Analysis, as demonstrated in Fig. 2.

Figure 2 represents the extent to which these conceptual clusters (factors) are associated. Only correlations above 0.25 are shown. One big cluster contains the discussions of the emergence concept with headings such as downward causation, causality, reduction, consciousness, evolution, hierarchy, complexity, complex adaptive systems, and governance. These interrelated concepts demonstrate both the field emergence and the aspects of emergence concept.

As explained in the literature review, different domains interpret various aspects of emergence by sticking to the logic and philosophy of the emergence concept. These different interpretations have made the concept more diversified and applicable to other domains.

In the second stage analyses, the keyword string (see "Appendix") is applied to explore the emergence research in science and innovation domains and 816 publications are retrieved from the WoS database. Then, NLP was applied to the abstract and title fields to parse the phrases, and 18,184 phrases, in total, were found. After applying stopwords and fuzzy matching, 16.683 phrases were reached with 96% coverage. Because the aim of this study was finding the usage of “emergence” and “emerging” words in these papers, the phrases containing an “emerg*” (stemmed, Boolean) expression yielded 130 phrases (with 57% coverage). When these phrases were analyzed in detail by reviewing the sentences in which they were used, it was seen that in 62 phrases the word “emerging” was used. In 10 phrases “emergent,” was used, and in 58 phrases “emergence” was used. As can be seen, an emergence concept was mostly used as an adjective in these studies to describe a noun with “emerging” and “emergent” words. Finally, we refined the list by considering phrases that included technology, science, and research, as demonstrated in Table 1.

When the sources of these terms were examined, 133 publications (115 articles, 6 proceeding papers, 5 book reviews, 4 editorial materials, 2 corrections, and 1 review) were found. As explained in the Methodology Section, these publications were downloaded and examined manually to detect different definitions for TE.

After full-text examination, it was seen that emergence or emerging technology phrases were used in 101 publications by authors just for distinguishing their focused research domain. These studies did not give a definition or cite any reference for discussing the conceptual definition of emergence. Therefore, 32 remaining publications (listed in Table 2) became the focus for further study.

The publications were classified into ‘Defined’ and ‘Cited’ groups. Some of the publications partially or fully defined emergence, and they were called ‘Defined’. Other publications only cited relevant literature and discussed it; they were classified as ‘Cited’. It can be determined from Table 2 that defining or citing emergence in selected articles started in 1988 and increased during the 2000s. In one study, Olleros and Macdonald (1988) used “emergence” to describe the track of new technology emergence from the laboratory to incubation, and commercialization. They did not define technology emergence formally but describe the process for business firms.

It was seen in reviewing the cited group, that Anderson and Tushman (1990), Cozzens et al. (2010), and Rotolo et al. (2015) were milestones for interpretation of emergence regarding technology. Mentioning lack of conceptual definition of emergence, Cozzens et al. (2010) began their study with explaining technological and scientific change in innovation studies. They reviewed emerging technology in literature and found its operational bottlenecks. Even though they did not propose a formal definition, this publication might be accepted as a milestone of its period. It should be noted that they did not examine the concept by searching the nature of emergence.

Rotolo et al. (2015) attempted to give a definition of emergence. They demonstrated the increasing number of publications and then cited dictionary definitions of emerging technologies. Even though they cited the philosophy of science and complexity theory references with a limited number of studies, their definition relied on the applied studies in which “emerg* technolog*”, “tech* emergence”, “emergence of* technolog*”, or “emerg* scien* technol*” were used in titles. After this lexical search their focus changed from “emergence” to “emerging technology” and gave twelve definitions of emerging technologies. However, when considering the “emerging technology” definition, they proceeded to use “technology emergence” interchangeably with “emerging technology”. Although they used it this way, it should be emphasized that reviewed literature has not supported this idea (Teran 2017). Beyond this discussion, they proposed uncertainty and ambiguity, coherence, radical novelty, prominent impact, and relatively fast growth as aspects of emerging technologies and defined emerging technologies

Table 2 List of publications (TA&SM: Technology Analysis and Strategic Management; TF&SC: Technological Forecasting and Social Change)

Selected titles	Publication year	Journal	Reference	Formal definition
Strategic alliances—managing complementarity to capitalize on emerging technologies	1988	Technovation	Olleros and Macdonald (1988)	Defined
Tracing emerging irreversibilities in emerging technologies: The case of nanotubes	2005	TF&SC	van Merkerk and van Lente (2005)	Defined
Characterizing the emergence of a technological field: Expectations, agendas and networks in Lab-on-a-chip technologies	2006	TA&SM	van Merkerk and Robinson (2006)	Defined
Tracking the evolution of new and emerging S&T via statement-linkages: Vision assessment in molecular machines	2007	Scientometrics	Robinson et al. (2007)	Defined
Asymmetric positioning and emerging paths	2008	Futures	van Merkerk and van Lente (2008)	Defined
Multi-path mapping for alignment strategies in emerging science and technologies	2008	TF&SC	Robinson and Propp (2008)	Defined
Nano-worlds as Schumpeterian emergence and Polanyian double-movements	2008	TA&SM	Randles et al. (2008)	Defined
Tailoring CTA for emerging technologies	2008	TF&SC	van Merkerk and Smits (2008)	Defined
Conceptualizing patterns in the dynamics of emerging technologies: The case of biotechnology developments in the Netherlands	2009	Technovation	van der Valk et al. (2009)	Defined
Emerging research fronts in science and technology: patterns of new knowledge development	2010	Scientometrics	Upham and Small (2010)	Defined
Emerging technologies: quantitative identification and measurement	2010	TA&SM	Cozzens et al. (2010).	Defined
A framework for mapping industrial emergence	2011	TF&SC	Phaal et al. (2011)	Defined
Emergent technologies, network paradoxes, and incrementalism	2012	Journal of Business Research	Low and Johnston (2012)	Defined
Dynamics of scientific knowledge bases as proxies for discerning TE—The case of MEMS/NEMS technologies	2013	TF&SC	Avila-Robinson and Miyazaki (2013)	Defined
Innovating via emergent technology and distributed organization: A case of biofuel production in India	2013	TF&SC	Surie (2013)	Defined

Table 2 (continued)

Selected titles	Publication year	Journal	Reference	Formal definition
Relative age of references as a tool to identify emerging research fields with an application to the field of ecology and environmental sciences	2014	Scientometrics	Jaric et al. (2014)	Defined
Examining open-endedness of expectations in emerging technological fields: The case of cellulosic ethanol	2015	TF&SC	Gustafsson et al. (2015)	Defined
Smart innovation policy: How network position and project composition affect the diversity of an emerging technology	2015	Research Policy	van Rijnsoever et al. (2015)	Defined
What is an emerging technology?	2015	Research Policy	Rotolo et al. (2015)	Defined
Public private partnerships and emerging technologies: A look at nanomedicine for diseases of poverty	2016	Research Policy	Woodson (2016)	Cited
The emergent dynamics of a technological research topic: the case of graphene	2016	Scientometrics	Klincewicz (2016)	Cited
Applying LSA text mining technique in envisioning social impacts of emerging technologies: The case of drone technology	2017	Technovation	Kwon et al. (2017)	Defined
Ethics of Emerging Information and Communication Technologies On the implementation of responsible research and innovation	2017	Science and Public Policy	Stahl et al. (2017)	Defined
A measure of staying power: Is the persistence of emergent concepts more significantly influenced by technical domain or scale?	2017	Scientometrics	Carley et al. (2017)	Cited
A patent search strategy based on machine learning for the emerging field of service robotics	2017	Scientometrics	Kreuchauff and Korzinov (2017)	Cited
Monitoring emerging technologies for technology planning using technical keyword based analysis from patent data	2017	TF&SC	Joung and Kim (2017)	Cited
An indicator of technical emergence	2018	Scientometrics	Carley et al. (2018)	Cited
Early identification of emerging technologies: A machine learning approach using multiple patent indicators	2018	TF&SC	Lee et al. (2018)	Cited

Table 2 (continued)

Selected titles	Publication year	Journal	Reference	Formal definition
Easing the assessment of emerging technologies in technology observatories. Findings about patterns of dissemination of emerging technologies on the internet	2018	TA&SM	Carbonell et al. (2018)	Cited
Insights into relationships between disruptive technology/innovation and emerging technology: A bibliometric perspective	2018	TF&SC	Li et al. (2018)	Cited

as “a radically novel and relatively fast growing technology characterized by a certain degree of coherence persisting over time and with the potential to exert a considerable impact on the socio-economic domain(s) which is observed in terms of the composition of actors, institutions and patterns of interactions among those, along with the associated knowledge production processes. Its most prominent impact, however, lies in the future and so in the emergence phase is still somewhat uncertain and ambiguous”.

A social approach to TE came with van Merkerk’s studies in which the emergence phenomenon was analyzed by considering the sociological side of emerging technologies. In their first study, emergence was defined as “… is the process or event of something coming into existence. For technological development this notion then relates to the very early stages of technological development” (van Merkerk and van Lente 2005). One year later, van Merkerk and Robinson (2006) proposed a networking perspective for deeper understanding of path emergence, and improvement of means to study early-stage technology fields. Then, van Merkerk and van Lente (2008) asserted positioning theory for studying patterns in emerging technological fields by considering a sociological perspective. In the same year, van Merkerk and Smits (2008) applied the Collingridge dilemma, in which it was stated that, in early stages, opportunities to steer are plentiful, but hard to choose from, while at later stages this was reversed, to emerging technology search. Moreover, they proposed to focus changing the actors and the interaction of actors involved in the innovation process of a specific emerging technology for understanding the process deeply. It can be stated that with van Merkerk’s studies, emergence in a technology context had added a sociological dimension.

In another study, Robinson and Propp (2008) proposed a path-dependent model for the early detection of emergence in science and technology by benefiting socio-technical paradigms. They again didn’t formally describe the “emergence,” but put forward uncertainty, dynamism, and multi-path approach aspects. Randles et al. (2008) proposed a convergence approach to detect technology emergence.

Different from Randles et al. (2008), van der Valk et al. (2009) questioned the patterns of technology dynamics of emerging technologies for conceptualization and they tried to contribute to technology emergence by considering technological diversity. They did not define, but approached with a different dimension to, technology emergence.

Upham and Small (2010) approached technology emergence by citing Derek Price’s invisible college definition. They added that for successful research fronts there would be two possible outcomes as areas grow independently or get “absorbed” by other areas. With this study, they tried to distinguish these outcomes by differentiating between research fronts that “emerge” by growing in size and fronts that are “absorbed” as a result of their papers being increasingly cited. Their understanding of emergence can be summarized as searching for growth and impact aspects of discrete topics. Phaal et al. (2011) used the term to identify industrial emergence and proposed a framework for mapping alternative roads to predict current and future emergence. They applied a linear perspective with an alternative future approach. They didn’t describe “emergence,” but applied the emerging industry definition from Michael Porter. The other industrial emergence study came from Surie (2013), and examined emerging technologies for developing a systematic approach to understand capability building and market formation dynamics. The subject was handled by utilizing complexity theory with its focus on interactions and interdependence, non-linear dynamics and emergence. Then, Surie (2013) asserted that non-linearity and adaptation made complexity theory relevant for understanding transitional phases in technological cycles and the evolution of highly complex forms and self-organization. Contribution on conceptualization of emergence here drew partially from the perspective of "industrial emergence".

In 2013, Avila-Robinson and Miyazaki (2013) used the term *TE* in their title, but focused on the identification of emerging technologies by using bibliometric approaches. They emphasized the formation, change, and transformation of knowledge as aspects of emergence by citing it in the literature review. The "year of emergence" was used as one of the variables in their methodology. They described it with a frequentist approach by considering more than ten publications accumulated for a particular field. From this aspect, it can be asserted that they described emergence with a quantitative and agglomerative aspect.

Jaric et al. (2014) characterized emerging research fields by a more rapid generation of knowledge, with results published in an increasing number of articles, and, as well, with shorter elapsed time between successive publications dealing with the same topic. Moreover they asserted that if the emerging front is characterized by a higher publication frequency, such boundary will span a shorter time interval, and will therefore be characterized by more recent publications. By quoting de Solla Price, they added that new knowledge seems to flow from highly related and rather recent pieces of old knowledge. They contributed to emergence conceptualization by hypothesizing that trends in the relative age of references might also be indicative of emerging research fields.

Gustafsson et al. (2015) aimed at contributing to the work on characterization and dynamics of expectations in emerging technological fields by advancing the heuristics on characterization of generalizations underlying guiding images and by disentangling expectations from anticipations. They tried to deal with uncertainty by examining different bases with underlying expectations and anticipations. They found that developers of emerging technologies partly based their activities on expectations retrieved from the past, but, on the other hand, that actors have visions that do not have strong backgrounds in past developments. They classified expectation as well-grounded inferences arising from the past, to the first order generalizations towards the future and anticipation as opportunities from second order generalizations. They asserted that this distinction between expectation and anticipation gave them opportunity to reflect further on emergent irreversibilities.

van Rijnsoever et al. (2015) contributed to emergence conceptualization by studying the influence of network position and the composition of collaborative innovation projects on the creation of an emerging technology. They found that more clustering contributes less to technological diversity and more to diffusion. Their contribution relates to a diversity aspect of emergence.

Kwon et al. (2017) described emerging technologies as consisting of unprecedented technological features with socially unaccepted functions, thereby containing complex and intangible characteristics within their nature. Their contributions treat social acceptance of emergence.

Stahl et al. (2017) explored the ethical issues related to emerging technologies and defined emerging technologies as "currently being developed and holding a realistic potential to not only become reality, but to become socially and economically relevant within the foreseeable future". With this quote, it can be asserted that uncertainty and unexpectedness might be better words for summarizing their contribution.

Carley et al. (2017) discussed different definitions of emergence and proposed to analyze persistence as a concept. They described it as a synonym for "staying power" in a technological time series. They tested the concept in 15 different sub-datasets for a dye-sensitized solar cell framework and found that domain and scale affected the persistence behavior. Therefore, it can be asserted that not every domain is appropriate for emergence research, and one-size-fits-all solutions may not work well. The other study was again by Carley et al. (2018) and in this study they proposed an indicator for technical emergence based on the indicator sets of FUSE and Rotolo et al. (2015). FUSE refers to the U.S. Intelligence Advanced Research Projects Activity (IARPA) Foresight and Understanding from Scientific Exposition (FUSE) Program [http://www.iarpa.gov/index.php/research-programs/fuse] that sought to devise indicators of emerging technologies. Carley et al. (2018) discussed the definitions of emergence by combining "emerging technology" and "emergence". They also put forward four aspects: (1) novelty—qualities of being new or original; (2) persistence—measuring a concept's ability to continue or endure; (3) community—a sense of group of people who show interest in a topic under scrutiny; and (4) growth—implying an increase over time.

Recent studies mostly cited emerging technology conceptualizations of Cozzens et al. (2010) or Rotolo et al. (2015), and tested different aspects of emergence in their studies (Carbonell et al. 2018; Carley et al. 2018; Joung and Kim 2017; Kreuchauff and Korzinov 2017; Lee et al. 2018; Li et al. 2018). Carbonell et al. (2018) defined emerging technologies by distinguishing them from technology trends as 'those technologies that have the potential to gain social relevance within the next 10–15 years'. They emphasized social relevance with this definition and contibuted by its exogenous social impact and acceptance.

Finally, it can be asserted that the nature of emergence and approximately 150-year philosophical discussions might be neglected by innovation and technology scholars. Moreover "emergence" and "emerging technology" concepts were used interchangeably as if they had the same meaning. Instead, emerging technology has been focused and unexpectedness, social acceptance, social relevance, persistence, diversity, network position, and uncertainty were emphasized while using emergence in innovation-related articles. However, only in Rotolo et al. (2015) was the emergence concept mentioned, but not formalized, while conforming an emerging technology definition. In the following section these discussion points are dissected.

Discussion

In essence, emergents present a generalized and profound phenomenon in nature, society, and even our universe; the relevant thinking and studies on the dynamic mechanisms of emergence involve philosophy of science, complexity science, economics, management science, and so forth. Although the acknowledged definitions of emergence are still hardly used for different research perspectives, some properties of emergence have reached a consensus in multi-academic areas—for instance, uncertainty, unexpectedness, self-adaptiveness, and self-organization. However, technological emergence (TE) is one of the popular application areas in technology management, and the theoretical and conceptual explorations of TE are still developing and unsystematic.

Studies related to the concept of emergence have been traced back to the 1900s. The divergence and convergence of this concept were qualitatively and quantitatively examined. Based on the aim of this study, understanding emergence in the technological context was also reviewed in focused journals. It was found that analyzed articles mostly accepted the emergence concept without formally defining it, except for one. However, in these publications, it seemed that scholars used the term for expressing unexpected and surprising events in a technological context.

Basically, the proximity between TE and economic emergence could be significant for the common drive for human economic behaviors. Regarding the dynamic mechanism of TE, economic behavior of the human is also a critical factor. From the perspective of emergence dynamics, TE is an unexpected phenomenon of self-organization and self-adaptiveness, and the uncertainty of TE relies on the unpredictable occurrence and scale of the emergent whole. In addition, TE could be defined into a rapid aggregation of large-scale personal, rational behaviors in a short time period, and the interactions and coupling effects between these factors (e.g., rapid aggregation, short time period, rational behaviors, personal interest, large-scale, etc.) form the complexity and uncertainty of TE.

It should be made evident that Cozzens et al. (2010)'s and Rotolo et al. (2015)'s studies were accepted as key attempts to define TE in the reviewed literature. Because they were accepted as the only conceptual studies, and both focused to give a definition of emergence, our discussion simply considered their findings. Cozzens et al. (2010) handle the concept with applied perspective and considered detection methodologies instead of giving a formal definition. However, besides methodology, Rotolo et al. (2015) described emergence in terms of five aspects. These are (1) radical novelty; (2) coherence; (3) prominent impact; (4) relatively fast growth; and (5) uncertainty and ambiguity. In reviewed philosophy and complexity literature, it can be asserted that all of these aspects were stated with different meanings or may be with a well-articulated definition.

For instance, the philosophy of science and complexity theory utilized novelty with its qualitative aspect. However, it was well-known that in the technological context, the qualitative aspect might be interpreted with its radical or incremental characteristics as stated by Rotolo et al. (2015). In this sense, the question is how to apply radical novelty as a criterion for forecasting TE as proposed by Rotolo et al. (2015). If technology didn't emerge, it may be hard to get the signals of the radical aspect of novelty in TE and judge it. Therefore, radical novelty might be accepted as a post-evaluation criterion for describing "emerging technology," which has already occurred and was qualitatively evaluated by specialists as it was.

Moreover, for understanding coherence, the whole and its parts should be defined for scientometric studies. We propose that coherence be understood with the continuity or the persistence aspects of technologies. From the continuity aspect, detection of irregularities might be important. However, it is clear that not all irregular trends lead to TE, but qualitatively novel ones might. In this aspect, novelty should be handled with its qualitative aspect. At this stage the question arises, "How can qualitative novelty occur in scientific networks?" Complexity theorist Goldstein proposed the creativity process be used as an analogy for this issue. Creative processes have a higher probability to produce TE. Therefore, describing creative networks in analyzed domains may decrease the noise of irregularities that are not qualitatively novel.

From another approach, scientific production may be understood from a sociological network perspective. As mentioned in evolutionary discussions by economists, the distinguishing side of the evolutionary perspective of economics is asserted to be that of humans and their judgments. Technology should also be evaluated with this interpretation. As explained in the knowledge production literature, technology development needs an accumulation of knowledge and interaction for different actors (Gibbons 1994). In this sense, synergy might be another important characteristic of these networks. Is it possible to claim that increasing synergy in scientific networks may increase the coincidence of the emergence possibility in scientific networks? Corning proposed that the synergistic effect may lead to emergence. However, synergy should be understood with its qualitative nature and increasing qualitative synergistic effects may lead to TE with higher probability.

Some assertions from the philosophy side come with an unpredictable aspect of emergence. This rule may be eased in technological contexts because producing scientific knowledge needs some preconditions—for example, the accumulation of knowledge in time, creative discussions and feedback, and the interaction of different actors. The knowledge production process may be traced with the help of "Big Data" analysis tools and online databases. As a result, some weak signals may be distinguished with appropriate tools and algorithms based on data relevancy, computational power, etc. In this sense, tracing scientific knowledge production may lead us to find these weak signals for reaching TE. However, defining the antecedents of TE is another important question which has not been well addressed in existing literatures. Without approaching from a processual rationale, it may be hard to predict TE appropriately.

Finally, there are four main discussion points that should be handled in future studies. These are:

1. What are the antecedents for TE from a processual perspective?
2. What are the predictive and descriptive[9] aspects of TE?
3. May qualitative synergy be applied to predict emergence in its earlier stages?
4. May scientific creativity be accepted as the anticipatory cycle that should be traced to reach TE?

Conclusions

Managers and decision makers in this connected age confront uncertainty and risk together. The fast-changing dynamic context highlights plenty of unknowns, and new instruments that translate them into knowledge require adaptive and proactive management. Therefore, researchers, industries, funding bodies, and policy/decision makers, both in public and private organizations, need to detect and track scientific progress in order to exploit arising opportunities and resultant risks. Recognizing these needs, many studies focused on exploring technical or technological emergence in science databases to help managers be proactive. This study aimed to trace the theoretical roots of emergence and find discussion points for understanding TE.

The emergence concept has not been formally described except in one review study. The concept has mostly been used to demonstrate unexpected and surprising events that can be accepted as a dictionary definition. However, it is evident that the emergence concept has been subjected to discussion since the 1800s. Unfortunately, this theoretical background on emergence has not shed strong light on today's limited TE treatments. In this sense, we extract points with inspiration from philosophy and complexity literatures that we propose as research considerations for future studies. When considering these questions, the nature of TE may be better understood, and with an increasing number of tools and methods, TE may feature increasingly in future applications.

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[9] We consider that Rotolo et al. (2015)'s study covers the descriptive part. Therefore, future studies might well focus on predictive aspects of TE.

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Appendix

Set	Results	Boolean expression
# 3	816	#2 AND #1
		Indexes = SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC Timespan = All years
# 2	206,968	TI = (emerg*)
		Indexes = SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC Timespan = All years
# 1	55,762	SO = (TECHNOLOGICAL FORECASTING "AND" SOCIAL CHANGE OR RESEARCH POLICY OR SCIENTOMETRICS OR TECHNOLOGY ANALYSIS STRATEGIC MANAGEMENT OR JOURNAL OF ECONOMIC BEHAVIOR ORGANIZATION OR ACADEMY OF MANAGEMENT JOURNAL OR FUTURES OR TECHNOVATION OR STRATEGIC MANAGEMENT JOURNAL OR INTERNATIONAL JOURNAL OF TECHNOLOGY MANAGEMENT OR MINERVA OR INDUSTRIAL "AND" CORPORATE CHANGE OR JOURNAL OF BUSINESS RESEARCH OR SCIENCE "AND" PUBLIC POLICY OR TECHNOLOGY IN SOCIETY OR LONG RANGE PLANNING OR POLICY STUDIES JOURNAL OR JOURNAL OF PRODUCT INNOVATION MANAGEMENT OR JOURNAL OF STRATEGIC STUDIES)
		Indexes = SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC Timespan = All years

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