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How radical is a radical innovation? An outline for a computational approach

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Abstract

Radical innovations prompt significant subsequent technological development and exhibit novelty and "architectural" innovation, i.e. rearranging the way design elements are put together in a system. Thus, radical innovations often serve as the foundation for new technological systems, industries or domains and are seen to involve significant conceptual breakthroughs, through either luck or genius. The much more common incremental innovations are perceived as mere improvements to existing technologies. Decreasing returns from incremental innovation are understood to motivate a search for a new radical innovation to provide a platform for more incremental innovation.

However, deeper study shows that the conceptual "distance" a radical breakthrough travels is far shorter than would initially appear. On closer inspection, several innovations with undoubtedly radical effects comprise several small inventive steps that appear self-evident, even logical, to the developers. This conundrum appears to stem from conflating a radical effect with a radical development. What's more, this view of radical innovation views inventions as isolated from the broader currents of technological development. An alternative view sees innovations as embedded in a co-evolutionary socio-technical landscape, where inventions develop in a technological environment and become building blocks for further inventions. Although only inventions adopted for use can be called innovations, "inactive" inventions can also serve as building blocks. In this view, (almost) all steps to innovation are incremental, but the system's self-organized criticality (SOC) allows spontaneous radical effects.

This work explores the importance of an evolutionary and SOC view of invention and innovation through agent based models. We develop a simple model capable of simulating the build-out of technologies in a series of simulation experiments. Although all inventions develop incrementally, the model behaviour is expected to exhibit SOC so that some inventions trigger much higher rates of subsequent development than others. Thus, the results are expected to

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support an evolutionary view of technological development where a radical effect is a consequence of the entire interdependent landscape rather than of the radical development of a specific innovation. The model should be of interest to several research streams concerned with simulating and studying R&D activities.

Keywords: Radical innovation; Incremental innovation; Technology adoption; Agent-based models; Self-organized criticality

1. Introduction

How novel technologies, or innovations, are developed and adopted for use remains an enduring subject in science and technology studies. Past research (e.g. [1]) concludes that innovations build upon each other and serve as foundations for new technological systems, industries or domains of knowledge. In this paper we examine technological innovations or "purposed systems" [1], which are any means to achieve a desired purpose, including technologies, processes, business models, and behaviors. We also state early and clearly that we ignore the distinction between the creation of new ideas and the implementation of them [2] and thus use innovation, rather than invention or technological change, for all stages of development and use. Many writers argue for these distinctions to be explicit through terminological choices, but our analysis makes them effectively meaningless.

Innovations are often classified as either radical or incremental (see e.g. [3], [4], [5], [6] and [7] for reviews) according to various evaluations of novelty or impact. Radical innovations are generally understood to have a high degree of novelty, being totally or substantially new, with the implication of being unique as well. Radical innovations are also identified with a profound effect on future development, establishing whole new fields of study, making dominant rival technologies or processes obsolete, and upending the status quo. Incremental innovations possess far less novelty, uniqueness or originality because they are considered mere modifications or refinements of already existing innovations. Incremental innovations may advance research but inspire no new fields, may increase the efficiency or capabilities of current technologies, but not make competitors obsolete, and uphold the status quo.

While seemingly intuitive, the differences between radical and incremental innovations are surprisingly difficult to pin down. What is "novel" depends on the particular innovation under study as each research team must decide to count the new-to-me among the novel, or restrict it to the new-to-absolutely-everyone, or to include innovations involving old components arranged in new ways, or to demand at least one new component in order to be considered novel. Novelty is consequently measured by subjective judgments of the degree of new knowledge contained [8], hoping to achieve an internal consistency in the judgments by a given team rather than a universal definition, although backward patent citations, showing the amount of ideas as well as the diversity of fields leading to a patent, are sometimes used to measure novelty or uniqueness. Impact on future development seems much easier to measure objectively, and perhaps partly as a result, many studies attach the label "radical" to those innovations that have had a significant influence on future science and research [3] [6] [9] [10] [11].

Although useful, these measures are fraught with problems and complications. Novelty judgments are very subjective and highly observer dependant, leading to a wealth of definitions to reconcile what should and should not be considered novel by different groups. Uniqueness and originality are similarly tricky; Kelly [12] finds that independent parallel discovery within a short time frame is the norm, rather than the exception, for almost every innovation. Impact measures, too, are distorted by limits made to mitigate the effects of time. For example, counts of forward patent or journal citations [11] might be limited to only those citations within 5 years of publication to prevent older patents appearing more radical through increased opportunities for citation, although as new patents are much more readily accessible though internet technology, the limit may do more harm than good. By limiting the counted citations, this method would incorrectly classify an obscure or slow starting radical innovation.

2. Defining the problem

The real problem, however, is that underlying measures of novelty or impact is an unstated and untested assumption about the nature of innovation development and implementation. Radical innovations are implicitly or explicitly seen to involve conceptual breakthroughs that are fundamentally different from the ideas behind incremental development. As Johnson says, "We have a natural tendency to romanticize breakthrough innovations, imagining momentous ideas transcending their surroundings, a gifted mind somehow seeing over the detritus of old ideas and ossified tradition." [13] Attempts to classify radical innovations are really attempts to travel backward along the assumed link between a major impact on human activity, science, or markets to the human genius, inspiration or creativity underlying a breakthrough in the development process. Unfortunately, when examined critically, the birth process of many "radical" innovations reveals only logical, even obvious, small steps with no "eureka" moments. On the other hand, many truly unprecedented ideas have been left unappreciated, mocked, ignored and vilified until the world was ready for them.

For example, the Outokumpu copper flash smelting process, introduced in the late 1940s and today considered one of the greatest metallurgical breakthroughs of the 20th century, grew from existing practice and the accumulation of research carried out since the 1890s [14]. While the Outokumpu process was an undoubtedly important innovation, it is difficult to isolate any conceptual leap in the methodical work (carried out in a matter of months) that was required to assemble the components of the innovation [14]. Similarly, the airplane was developed by the Wright brothers [15] [16] as a result of many small, individually unremarkable technological experiments in a logical progression, with no readily apparent "conceptual leaps" as implied in the innovation literature. Both of these "radical innovations" appeared novel, unique, and conceptually distant from rival technologies, despite undoubtedly being developed incrementally. As a further contrast, Bradshaw [16] notes that many unsuccessful contemporaries to Wright brothers attempted the "conceptual leap" strategy of testing complete aircraft designs. To doubly dissociate the development and effect of invention, there are cases of genuine, original thoughts, devised by lone geniuses, which languished in obscurity for until a time when they represent the next, logical step. For example, Charles Babbage's Analytical Engine predated the first general purpose computer by over 100 years [13] while Gregor Mendel's theory of trait inheritance was rejected until independent discovery of the theory well over a century later. It seems that truly radical conceptual breakthroughs may be dismissed until incremental development catches up to provide a context that can support them.

Upon noticing the dissociation between development and effect, researchers have tried to refine the ways that development can be considered radical. Henderson & Clark [7] conclude that radical and incremental are extremes on one dimension for components and another for the arrangement of them, so that an innovation with no new components but a major impact, such as the Outokumpu smelting process, can still be called radical. Instead of zooming in and redefining what counts as radical in the development process, others zoom out and effectively dispense with the need to locate a conceptual breakthrough by substituting measurements of innovator characteristics. Since Schumpeter [17], researchers (e.g. [9]) have all statistically linked characteristics such as firm size, age or R&D strategy to the likelihood of producing innovations with radical effects. As a result, these characteristics have been used as measures of the radical potential in the development process. But all of these suffer from the underlying assumption that any innovation with a radical effect must have involved a radical departure from the past.

This romanticized assumption probably comes from the difficulty of observing innovation activities as they happen. With certain exceptions (e.g. [18]) researchers have mostly been confined to retroactively classifying innovations for which there is knowledge available, favouring the most successful innovations (which also tend to be the ones with most information available) and colouring their views with the knowledge of future success. It is easy to see how a researcher, looking back in time and without first-hand knowledge of the field, might see the innovation as an isolated, conceptual leap ahead of the state of the art, conforming to the image of a lone scientist with a flash of inspiration, and ignoring how information, ideas, conceptualizations of a problem or possible solutions flowed around, half-formed, and constantly, subtly reshaped through a protracted, incremental development. But viewing inventions as isolated epiphanies doesn't hold up well to scrutiny. In fact, we question the idea that innovations that turn out to have major impacts are fundamentally non-incremental, that they are any more unique or original, or that there is some intangible quality that figures, either as luck or genius, into the process.

3. Proposed alternative

We propose that inventions and innovations are not independent introductions to a waiting world, but instead are interacting entities in the constantly shifting socio-technical landscape of a Complex Adaptive System (CAS). This landscape of past and present inventions is shaped by research programs, problems needing solutions, and the costs of energy, materials, parts and labour. Every invention is an incremental step in a wander through the landscape, and every step taken distorts that landscape. The movements and resulting shifts create or destroy links along which materials, information or influence flow, ameliorate some problems and make others worse. These inventions compete with close neighbours for utility, advantage and popularity, but can also become building blocks for distant inventions, even if they never succeed as standalone inventions. The statistical relations found between characteristics of inventors or development approaches and impact do not indicate a conceptual breakthrough in development, but reveal an attractor in the fitness landscape. As part of a CAS, the attractors are neither permanent nor independent so the characteristics linked to success will also shift and react to the rest of the system.

Even when all steps in the socio-technical landscape are incremental, some trigger big changes as a consequence of the capacity of CAS for emergent behaviours and self-organized criticality (SOC). Thus, some innovations result in spontaneous radical effects and returns while others do not, just as when roughly equivalent grains of sand added to a pile can either stick or precipitate an avalanche. And, just as avalanches, earthquakes, meteor strikes, cracks in pavement and many other phenomena follow power law distributions, so too do patent citations, scientific journal citations, and other measures of innovation impact [19], see also [20]. This strongly suggests that the frequency of major impact innovations varies as a power of the impact size of that innovation, meaning that the impact of an innovation has more to do with the impact (or lack thereof) of all the preceding and concurrent innovations in the socio-technical landscape than with the innovation itself. Many researchers have already begun to consider innovation as a CAS and SOC has been found to emerge in models of uniform technological development [20] [21].

Because innovation is inherently "messy," and CAS are non-intuitive, researchers are using the excellent new tools developed in computer modelling, especially in agent-based modelling (ABM), to study the unpredictable, chaotic, and evolutionary behaviours in dynamic environments. Theoretical "toy model" systems of innovation have been studied for more than a decade [21] [22] [23] [24] [25] [26] [20] [27] [28] [29] [30], allowing researchers to observe the entire dynamic process "in silico", without a bias toward successful innovations, rather than "post mortem" observations of various successful or – less often - unsuccessful projects. As a framework, most of these studies used variations of the NK model [31] or lattice percolation models [21].

While conceptually simple and relatively easy to implement, these models have some limitations and are difficult to extend beyond their current usage. The NK models usually assume an incremental search in a landscape where technologies are treated as independent from each other, not requiring "precursor" technologies. The absolute fitness of a technology never changes, despite newer developments. While co-evolutionary effects could be approximated by linking two NK models (the NKCS model), studies using the NKCS remain rare [32]. Percolation models typically represent technologies as lattice spaces that are either discovered, discoverable, or undiscoverable [21] and require an unbroken route of previously discovered technologies to become discoverable. This can replicate the "keystone" role played by relatively few patents [21] and the usual two-dimensional lattice could be generalized to n dimensions to model co-evolutionary effects, but more dimensions means more difficulty and fitness is typically an unhelpful, one-dimensional score tracking distance from starting point.

Arthur and Polak [20] introduced a promising alternative that elegantly combines the best features while mitigating the drawbacks of the NK and percolation models. Their logic circuit model satisfies predefined goals via combinations of "primitive" circuits and adds the developed circuits to the repertoire for use as future components, thus "bootstrapping" simpler technologies to make more advanced ones. The resultant network of elements and behaviours closely resembles the patterns of buildout and evolution in real-life technologies [1]. While this model allows some extension, it is relatively difficulty to implement, debug or program in alternative programming languages, while other extensions would be very difficult to include, and consequently, the model has so far seen surprisingly little use [1] [20] [33].

4. Methodology

We therefore present the "Adder" model, a simplification of Arthur & Polak's model implemented on NetLogo platform. The Adder replaces the logic circuits with simple arithmetical expressions, but retains important features and is easier to implement, understand, analyze and extend. This simplified model and easy to use ABM platform invites a broader community with less experience in computer programming to explore new model dynamics and parameter spaces in computational innovation research. However, as this model is still in development, we outline the model setup and operation, expected model behaviours, and some discussion of the potential uses of the model rather than finalized experimental results.

4.1. Overview of the model

Technologies are represented as strings of twelve components separated by the arithmetic operators + and -. At the beginning, the only available technologies is one seeded "primitive" technology, the number 1, and a random starting technology combined from the primitives and zeros, such as (0+0-0+0-0+0+0-0+0-0-0+1 = 1). At each time step, the agents select the best technologies from those available technologies for incremental modification by changing the sign of one operator or by replacing one component in the string with a technology drawn randomly from the pool of available technologies. The resultant technologies are then evaluated for fitness against cost, competition and how closely they match predetermined integer goals, before being added to the repertoire of possible components. The goals represent the needs that drive technology evolution, simplifications of logical operator needs used by Arthur and Polak [20]. The process continues until specified conditions are satisfied.

As an example, let us assume that one of the goals is "10" and that the pool of available technologies consists of only primitives (1), the random starting technology (0+0-0+0-0+0+0-0+0-0-0+1 = 1), and one other technology, (1+1-1+1+1-1+1+1 = 4). Our developer agent can modify any of the technologies available (the primitives or the available "4" technology) by adding, removing or changing one digit or operator, and so creates the new technology 1+1-1+1+1-1+1+4 = 7, by substituting the final primitive with the "4" technology. This new technology produces "7", and therefore is closer to the goal of "10". But closeness to the nearest goal is not the only way to rank fitness. Another would be the "cost" of the technology. In our model, the cost is equal to the number of primitive elements required. To continue the above example, if primitive components (1's) have a cost of 1, then the "4" technology above would cost 8 and the "7" technology would cost 15. Technologies could develop to become fitter by getting closer to a goal or by reducing the cost. The "4" technology could be superseded by several generations of more efficient technologies, with the ultimate limit of efficiency being 1+1+1+1, with a cost of 4.

4.2. Details for the basic model

We now describe the detailed algorithm for the simplest version of the model. It assumes one developer agent, predefined, equally spread goals, and single digit or operator modification, and the selection of technologies for modification is based on a closeness-to-goal and least-cost fitness. Additions and alterations mentioned above are omitted for the sake of clarity.

- At each time step, the model creates the active repertoire of technologies from the primitives, all developed technologies that are in the top X fittest technologies per goal, and all technologies used by any technology (recursively) in the top X fittest for a goal. For example, the "4" technology (with a cost of 8) used by the "7" technology would be included, even other "4" technologies had a lower cost, provided that the "7" technology was still in the top X fittest.
- The developer agent selects the top three fittest technologies for each goal. The fittest is copied six times and each copy is modified by a single change (changing one component for another from the pool or changing an operator) to create a new technology. The second fittest is used to create 3 modifications and the third fittest is used to create only one modification.
- The newly created technologies have a fitness calculated based on the distance to the nearest goal and cost calculated and are assigned an unique serial number reflecting the closest goal, the number produced, the technology they are a modification of, the level of competition per product (e.g. "4b" for the second technology to produce 4) and other features as needed per experiment.
- With 10 new technologies created per goal, many technologies will be bumped out of the top X fittest, and they, as well as any non-top X fittest technologies that they used are eliminated as the new current repertoire of technologies is created.

5. Expected model behavior and uses

The number of developer agents working to modify technologies and their interactions, the way they modify, the manner of determining which technologies to modify, the number and placement of goals and the way to determine fitness are among the variables that we plan for experimentation, once the model is complete. As the model implementation is still some way off, this list is based on the behaviours reported by [20] and on the behaviour of other, similar model.

Similarly to the original model, the Adder will exhibit "bootstrapping" behaviour in the buildout of technologies. Specifically, the model will start with primitives to build simple technologies, before using both primitives and simple technologies to build more complex ones. If the technologies are limited to a maximum of 12 components, then a goal like "24" cannot be developed before - at least - technology "2" has been invented. The reserve of developed technologies is expected to grow monotonically, but the number of technologies actually in use is expected to decrease as newer technologies or limiting conditions render old technologies obsolete. Finally, the buildout of technologies is expected to exhibit SOC behaviours as some "keystone" technologies trigger much higher rates of subsequent development than others, as the real-world analogues of steam engines, microchips or lasers have done. Obsolescence will cause "avalanches" of creative destruction as the sub-component technologies of recently obsolete technologies become obsolete as well. The original model [20] exhibited SOC in both the buildout and obsolescence of technologies using a random search strategy, but the Adder will provide an opportunity to test whether this applies equally to an incremental search.

The advantage of using the Adder over Arthur and Polak's original model is the greater ease of implementation, alteration, tuning and analysis. Whereas logic circuits tend to be difficult to analyze, technologies in the Adder model are eminently easy to understand and compare with simple mathematical techniques. For example, the lowest possible cost of a given technology is always trivial to determine: if the only allowed operators are + and -, the lowest cost possible equals the "product" of the technology itself. This not only makes programming easier and lowers computing requirements, but enables modification such as "rational agents" who can calculate how to reach a given goal. Furthermore, the rationality of the search can be easily adjusted by altering the input they use for calculation, the rules they use to calculate, including noise in their calculations, or by assigning some components by random draw and others with the benefit of pre-calculation. This in itself is a great advantage over most existing models of technological evolution, which tend to assume either fully random or completely rational development.

Other fine-tuning and extension options include replacing predetermined or random goals with dynamic goals (which retreat as technologies come closer), various modification schemes (e.g. allowing incremental modification of some components but not others at various stages of the experiment), the inclusion of instability in developed technologies (to represent scarce resources, the destruction of knowledge resources or restrictions in a use of a technology), different fitness evaluations, costing schemes or criteria for selection, and the addition of multiple developer agents with isolated or semi-isolated repertoires to test the effects of competition, patent protection and specialization. As the Adder is relatively simple, it can also be adapted for more complicated simulations, e.g. for studying optimal pricing policies for new technologies.

6. Conclusion

In this paper, we examine and reject the assumed link between conceptual breakthroughs during development and a major impact following implementation. As an alternative, we present a view of innovation as a purely incremental process of bootstrapping and modification in a complex adaptive system, and which exhibits emergent, radical effects as a result of self-organizing criticality. Furthermore, we have presented a way to test this view of innovation as a CAS with SOC through a simplified version of a groundbreaking model by Arthur and Polak [20]. The resulting model is simple to understand, implement, analyze and extend, and it significantly ameliorates the shortcomings of mainstream models in computational innovation research. We have also outlined some possibilities for testing and further extending the model that should provide plenty of opportunities for further computational innovation researchers.

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