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Tipping points in science: A catastrophe model of scientific change

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ABSTRACT

In this paper we discuss the capabilities for scientific knowledge to demonstrate explosive growth in short periods of time. In one notable example the field of engineering and technology management grew more rapidly in the 4 years after 1980 than it was expected to grow for the next 40 years. We provide 22 examples drawn widely from science, demonstrating that this phenomena is pervasive throughout science. We propose a new model, based on the idea of folds from mathematical catastrophe theory, a phenomenon that is more popularly known as tipping points. This model is then fit using non-linear regression in the presence of Poisson noise. While the tipping point does not occur in all fields of science, in those cases where it does occur the resultant model overwhelmingly supports the idea of catastrophic growth within scientific knowledge. We describe the differential equations underlying the fold catastrophe and relate these equations to a process of communication and interaction. We relate this dynamic to other word of mouth models such as the Bass diffusion model. We further discuss why scientific, and to a lesser extent news, articles are subject to this behavior while the same phenomenon is unlikely to occur when solely measuring the sales of a physical product. We provide evidence of the phenomenon in one brief sociological sketch of scientific activity. Finally, we discuss the relevance of the model in terms of innovation forecasting. In particular, we evaluate the possibility for ex ante anticipation of the bifurcation point.

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Introduction

The field of scientometrics attempts to create both static and dynamic measures of knowledge production. Previous scientometric research into dynamic measures of knowledge production has examined a range of alternative measures including word usage (Noyons and van Raan, 1988), citation usage (Boyack et al., 2007; Garfield, 2004), and patterns of collaboration (Reid, 1997). Scientometricians often use a sociology of science perspective when modeling the growth of knowledge (Zitt, 1991). This perspective, in turn, is strongly influenced by semiotics and linguistics (Rip and Courtial, 1984; Zitt, 1991). Our principal concern in this paper is the quantitative modeling of the growth of scientific knowledge. This concern in scientometrics dates to the onset of the field, and is perhaps best credited to the great philosopher and sociologist of science Derek de Solla Price. In this paper we discuss the capabilities for scientific knowledge to demonstrate explosive growth in short periods of time.

Studying the dynamics of science can be done at different levels of granularity. For example, one can look at the past development of a scientific field, at the research front currently faced in a particular research field, alternatively, one can study the broader disciplinary structure of the sciences, or instead in much more detail delve into a subfield and its dynamics. That is, one can study, the disciplinary structure, the fields within a discipline, the subfields that constitute a field, and research topics in a particular subfield (van den Besselaar and Heimeriks, 2006). Much of the current literature on science dynamics is of the macro-dynamic character. This literature is significant both for policy as well as of science. de Solla Price's (1961, 1963). contributions are of this character, and the work of Katz and Hicks (Hicks and Katz, 1996) representative of the policy relevant strand of research.

De Solla Price, musing upon a complete collection of the *Philosophical Transactions of the Royal Society of London*, observed that science has been growing exponentially. These observations were first noted in a 1963 book and then more famously in his 1963 work *Little Science, Big Science* (de Solla Price, 1961, 1963). This later book, which endorsed quantitative methods for analyzing science, fortuitously occurred at the birth of a new discipline of scientometrics. Not surprisingly, given its time and its content, the book became a citation classic for the field (de Solla Price, 1983).

De Solla Price, who was trained as a physicist, well knew the consequences of unending exponential growth. In de Solla Price's own words "the exponential growth business needled me a lot (de Solla Price, 1983)." He therefore postulated that eventually science must reach a steady state. His argument is that there is a finite population of potential scientists. Further, there will be decreasing returns to productivity as increasing numbers of scientists are trained and recruited by society. This occurs because of a gradation in scientific talent. The first scientists are the most talented, and are therefore trained in the most cost-affordable manner, producing the greatest marginal gains in scientific output. Recruitment and training for subsequent scientists becomes more difficult, with lesser gains in output achieved a greater expense. Publications here are taken as a measure of scientific output. De Solla Price, like many others after, understood the limitations of publication as the sole measure of scientific output. Nonetheless he convincingly describes the use of publication output as a partial indicator of scientific progress.

The logistic curve is an obvious choice for modeling diffusion limited growth. The dynamics of the logistic are compounded from two processes. The first process involves growth in proportion to an existing population. This is variously known as the dispensatory or replication process. The second process modifies the growth so that, as the population approaches its limit or stable carrying capacity, the growth rate approaches zero. The second process is known as the compensatory or inhibiting process (Miranda and Lima, 2010). The combination of these two processes results in the characteristic S-shape curve. Growth starts low, expands rapidly, passes through an inflection point, slows down and asymptotically approaches a saturation limit. See Fig. 1 for an example of how this might apply to the dynamics of publication output.

Verhulst first studies this dynamic in light of population biology (Verhulst, 1838). These dynamics were later rediscovered by Pearl (Pearl and Reed, 1920). Fisher and Pry described technological substitution behavior in light of logistic growth, although without direct reference to the earlier ecological applications (Fisher and Pry, 1971). Pearl and Fisher Pry curves are one form of trend extrapolation among many referenced by a premier text on technological forecasting.

Particularly noteworthy for our purposes are those papers which attempt to forecast growth in science and technology (Bengisu and Nekhili, 2006; Daim et al., 2006). This work serves a useful