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Description	一般論文

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Towards a general model of technological forecasting

— the Lotka-Volterra systems

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Abstract:

We recapitulate several challenges to the study of technological forecasting and changes and suggest that studies of diffusion of technologies must increasingly take into account interaction between new and other existing technologies or institutions. This paper revisits the Lotka-Volterra (LV) system and proposes that it may serve as an alternative formalism to start with in order to address the *multi-dimensional* aspect of technology diffusion.

1. Introduction:

Diffusion of technology is an important aspect of technical change. Without diffusion, innovations or new technologies have little social and economic impacts. Study of diffusion process however is not trivial. There are several major complications as have been cited in the existing literature:

1). A taxonomy[1] of innovation categories is hard to come by and agreed upon among students of technology; diffusion of minor improvements of an existing process seems to be different from diffusion of a new invention such as the electricity. How to characterize the differences between the two types of innovation? What different general approaches should be used to study diffusion of these and other different innovations?

2). New innovations hardly diffuse into a vacuum; along its growth trajectory, an innovation interacts with existing socio-economic institutions and with existing technologies largely due to cannibalizing existing techniques or products;

3). Diffusion is generally interlinked with more or less incremental improvement of the innovation itself *simultaneously*. At early stages, new innovations are badly adapted to many of the ultimate uses to which they will eventually be put [Rosenberg 1982]. Users provide many feedbacks as of how should the innovation's functional performance be improved. The diffusion process is therefore not passive but interactive between users and suppliers of the innovations. The innovation is not static;

4). There is no precise way to define the ultimate *scope of application* of a new innovation. Kodama [2000] suggested that some innovations create their own "use system" in the course of their diffusion; Watanabe and Kondo [2003] called some innovations as self-propagating as their features and applications are continually generated as they interact with the institutions. In biological terms, the technologies can be thought of starting in an initial niche and moving progressively to other market niches thus enlarging the scope of their applications.

5). The above have only made a passing reference to the effect of institutions on diffusion of technologies. In fact, the more pervasive and long term the innovation under consideration is, the more its diffusion will be subjected to institutional and evolutionary constraints, the innovation and the institution will constrain and shape each other. Diffusion of such innovations therefore is better portrayed as co-evolutionary.

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[1] See, however, Freeman [1992] on his categories of innovation in his studies of technical changes. He proposed four categories of technical changes in increasing effects or pervasiveness as: incremental innovations; radical innovations; technological systems and changes of techno-economic paradigms

Having acknowledged all these challenges and complications, a smooth S-shaped diffusion trajectory, which describes a relatively slow early change, followed by steep growth and then a turnover as size asymptotically approaches the saturation limit, while universally true, seems to abstract away too many important features of the diffusion process. Many "innovations" have since then been introduced to better model the diffusion of innovations. In this paper, we focused on two specific but versatile extensions of the familiar single logistic diffusion curve formalism[2]: a) the logistic curve with a dynamic carrying capacity and b) a system of coupled diffusion curves or the LV formalism. We briefly review each of them in turn.

2. Existing works:

Logistic with dynamic carrying capacity.

An introductory but seminal paper of the logistic with dynamic carrying capacity is that of Meyer and Ausubel [1999]. As explained above, whatever empirical definition of potential adopter one takes for some innovations or technologies, their number tends to increase over a certain time after the introduction of the original technologies due to that new applications are continually being generated. The representation of the carrying capacity in an otherwise simple logistic model therefore needs to admit its own dynamics. Meyer and Ausubel's formulation is to specify a logistic growth for the carrying capacity itself:

$$\frac{df(t)}{dt} = bf(t)\left(1 - \frac{f(t)}{K(t)}\right)$$

$$\frac{dK(t)}{dt} = a_K\left(K(t) - K_1\right)\left(1 - \frac{\left(K(t) - K_1\right)}{K_2}\right)$$

where K(t) denotes the carrying capacity which ranges from K_1 to K_2; f(t) is cumulative diffusion or installed base.

One pioneer example of application of this formalism to the study of innovation management is that of Kodama [2000]. He studied the diffusion pattern of different products such as fax machines, liquid crystal displays, personal computers and found that the diffusion of the personal computers can best be described by a logistic with a dynamic carrying capacity and concluded that diffusion of IT technologies can best be characterized by new business models creation rather than simply passive replacement mechanism as in the cases of the diffusion of fax machines and LCD.

In an earlier paper [Nagamatsu, Watanabe and Shum 2004], we proposed to study the diffusion trajectory of the PV industry in Japan. Our initial understanding of this technology is that it is self-propagating since its many features are developed as it diffuses and interacts with the potential adopters or users community. Important factor(s) for the diffusion of PV is the cost of PV in general and government's subsidiary in R&D for the case of Japan in particular. This understanding is, however, qualitative in nature. Using the past 25 years of diffusion data [see Fig. 1], we found that these data can best be fit into a Gompertz logistic with a dynamic carrying capacity. What is novel in our paper is that we have explicitly considered the change or increase in the carrying capacity as a function of the cost-learning and government policy to build up technological stocks in the PV technology, as captured by a *multi-factors learning function*. This gives a better micro-economic underpinning of the underlying dynamics of the carrying capacity.

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[2] Even within the single logistic formalism, many refinements can be obtained. For example, among different models that can generate the S curve pattern, the Fisher-Pry model predicts characteristics loosely analogous to those of biological system growth and is referred to as a substitution model; the Gompertz model, while also is S-shaped, is asymmetrical, and is usually used to refer to growth due to replacement process. One intuitive difference between the two is that in the Fisher-Pry case, initial installed base will facilitate future sales, there is increasing returns to adoption; on the other hand, in the Gompertz case, initial installed base do not make future adoption process better. An older technology is replaced by a newer technology that performs the tasks with essentially the same financial and or functional efficiency [Porter et al. 1991]

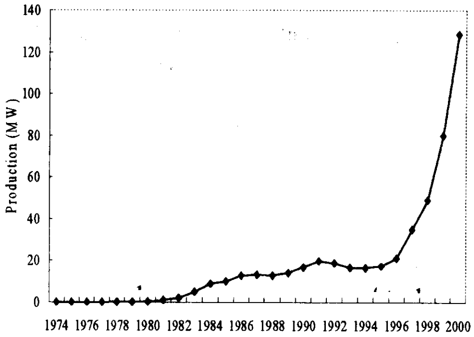

Fig. 1. Trends in PV production from 1974 – 2000 in Japan.

The resultant estimate of diffusion trajectory and carrying capacity are shown in Fig. 2. It shows that the resultant estimate of the diffusion trajectory fits very nicely to the actual data. In addition, the estimated carrying capacity maintained a nice margin enveloping both the estimated diffusion and actual diffusion data. This demonstrates the validity of our economic reasoning and our procedures.

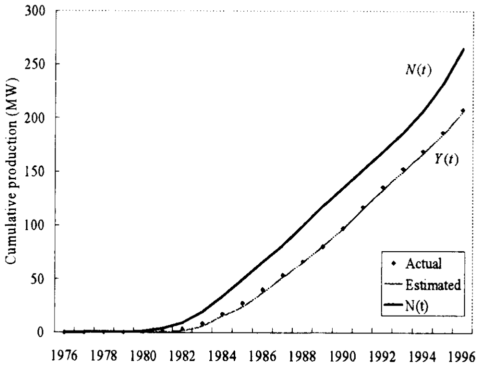

Fig 2. Empirical works showing the dynamic carrying capacity of PV diffusion trajectory in Japan during 1976 to 1996. Actual = diffusion trajectory; Estimated = projected diffusion trajectory from a diffusion model with carrying capacity modeled as driven by multi-factors learning; N(t) = estimated dynamic carrying capacity. [Nagamatsu, Watanabe and Shum 2004]

While these applications demonstrated the increasing sophistication of using the logistic with a dynamic carrying capacity to aid our understanding and characterization of the diffusion process, it is still deemed lacking in that it can not address the multi-dimensional aspect of diffusion of pervasive technological systems as stated in the introduction. One possibility is to consider introducing coupled logistics into our tool set.

The Lotka-Volterra (LV) systems

The original idea of the Lotka-Volterra equations is to model the evolution of interacting populations in an eco-system. Specific version of this set of equation includes the predator-prey model in which the interaction between the populations is of a *competitive* nature. A system of Lotka-Volterra equations is basically a coupled system of diffusion logistics describing the interactions between two technologies. More advanced versions can include more technologies or to introduce more realistic interaction terms among these technologies.

$$\frac{df_1(t)}{dt} = b_1 f_1(t)\left(\frac{K_1(t) - f_1(t) + \alpha_{21} f_2(t)}{K_1(t)}\right)$$

$$\frac{df_2(t)}{dt} = b_2 f_2(t)\left(\frac{K_2(t) - f_2(t) + \alpha_{12} f_1(t)}{K_2(t)}\right)$$

α's are the terms that describe the interaction among the technologies in the system.

It is important to clarify that a LV system is limited to a few closely interrelated technologies or markets and is a relatively closed system ignoring other *exogenous* influences. It therefore necessarily abstracted away other details and focus on the modeler's primary interests. Watanabe, Kondo et al. [2003] modeled the transition from analog to digital TV as a substitution process. One of the variables in the two-dimensional LV system is the population that has adopted the digital TV technology. The LV system better captured the interaction between the new and old broadcast technologies and gave more *information* about the actual diffusion scenario of digital broadcasting. On the other hand, a stand-alone diffusion logistic is also obtained for the digital broadcasting technology. The discrepancies in diffusion patterns as obtained by these two modeling formalisms are then explored from a policy or even institutional standpoint in order to guide the provision of *complementary efforts* to remove the inconsistencies between the two trajectories. What is clear in this example is that a LV system will always yield more realistic diffusion scenario for a new innovation than a naïve single diffusion trajectory. However, what is unclear is how to formulate the LV system in the first place. The next section attempts to address this issue.

3. Methodological synthesis:

In this section, we generalize the above example and propose a LV system of degree *n* to model the diffusion of a particular innovation within a particular technological system, subjected to a general set of constraints such as competition from other innovations, substitution from earlier versions of the same innovation and institutional conditions. The inherent nature of this LV system is that it captures the co-evolution aspect among all these relevant factors.

$$\frac{df_i(t)}{dt} = b_i f_i(t)\left(\frac{K_i(t) - f_i(t) + \sum_{j \neq i} \alpha_{ji} f_j(t)}{K_i(t)} \right)$$

$$\forall i = 1 \to n$$

Note that the f's above can refer to technologies or other *institutional processes*. One such institutional stock process, in the context of study of diffusion of self-propagation processes, is that of the dynamics of the developer population. It is conceivable that the availability of third party developers working on developing such a technology or a platform will exert a great influence on its diffusion; in turn, the more successful the technology, the more developers it will attract. This clearly suggests a co-evolutionary mechanism. In addition, the carrying capacity of each of these processes may be subjected to changes endogenously. This provides yet another modeling capability of the LV system in that it can generate more complex behaviors that may mimic the actual diffusion phenomenon.

4. Summary:

This paper attempts to outline some extensions of the single diffusion logistic formalism in order to address the inherent complexities of modeling diffusion of innovations. We have done this by 1) enriching the single logistic with a dynamic carrying capacity with a further specification of the change mechanism of the carrying capacity and 2) adding more degrees of freedom or dimensions to allow modeling interaction between the original innovation and other technologies in the diffusion environment via the Lotka-Volterra formalism. Future methodological innovations in modeling diffusion of innovations can be in terms of creative combinations of these two basic routines. The possibilities are endless. One remaining challenge then is data availability that can support such innovations in diffusion modeling.

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