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Technological innovation, business cycles and self-organized criticality in market economies

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Abstract – In the market economies, sustained output growth is always accompanied by persistent fluctuations. Whether the fluctuations are caused by external shocks or deterministic forces has been a controversial issue in economics, with the dominant mainstream paradigm favouring the former. Here we examine the hypothesis that an important determinant of periods and sizes of expansion and recession is the constructive and destructive effects of innovations and the consequent chain reactions. We show that an evolutionary two-dimensional Bak-Sneppen model is able to generate results which are very similar to the empirical fluctuations which we observe in GDP dynamics of OECD countries. The finding provides a different framework for understanding aggregate market dynamics from that of conventional economic theory.

Introduction. – Capitalist economies evolve in a way such that aggregate output grows in a sustained manner, with persistent fluctuations of varying amplitudes around this underlying growth. There is a growing consensus in economics that economic growth mainly comes from capital accumulation and from technological progress [1]. In contrast, there is much controversy over the sources of economic fluctuation.

The seminal work of the current mainstream theory of economic fluctuations is the real business cycle (RBC) theory proposed by Finn Kydland, Edward Prescott and other economists [2]. This theory regards exogenous technological disturbances as the source of economic fluctuations and argues that economic fluctuations are the outcomes of the responses of rational individuals to the disturbances. A problem with the theory is that even many mainstream economists find hard to accept that there can be negative technology shocks, we cannot see them in reality. As Gregory Mankiw pointed out: "My own reading of newspaper, however, does not lead me to associate most recessions with some exogenous deterioration in the economy's productive capabilities" [3]. More recently, RBC models have been extended into dynamic stochastic general equilibrium (DSGE) versions. DSGE models attempt to incorporate features such as sticky prices, but their basic rationale is the same. A recent survey of such models can be seen in ref. [4].

Besides theoretical explorations, empirical studies have been carried out in parallel. With the development of extensive databases, some techniques of statistical physics can be used to analyze macroeconomic performance [5–7]. In particular, such kind of applications may be helpful for understanding economic fluctuations. Ormerod *et al.* and Gaffeo *et al.* analyzed annual real per capita GDP data of 17 leading capitalist economies from 1870 to 1994 and concluded that the frequency of the recession periods is consistent with a power law [8,9]. Wright raised a query on this conclusion and contended that an exponential law fitted better [10]. In order to clarify the controversy, Ausloos *et al.* used quarterly GDP data of 21 countries in OECD from 1989 Q1 to 2003 Q2, a high-frequency data, to examine the distribution of recession periods and preferred a power law [11]. In addition, the case of prosperity periods was also investigated and a power-law distribution was found. Following these researches, Redelico *et al.* provided the evidence of Latin American countries [12].

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However, these researches are not enough to uncover the dynamics governing economic fluctuations. In this paper, we analyze quarterly real GDP data of OECD which include more countries and span a longer time period than those of Ausloos *et al.* to obtain some empirical facts on economic fluctuations, and specifically the periods and sizes of recessions and expansions. Then, we employ an evolutionary model based on the two-dimensional Bak-Sneppen model [13,14] and make comparisons between empirical facts and the results from the model.

The data. – The data we used is taken from the database OECD.Stat, where quarterly real GDPs of every member of OECD are available. GDP is calculated in terms of US dollars, adjusted by fixed PPPs. The time period for the most countries is from 1960 Q1 to 2009 Q1. Summing up the data points of all members, we have a total number of 5190 observations[1].

First, we calculate the average growth rates for each country. Suppose the available data of GDP for a country last over N quarters, and the growth rate of the i-th quarter is r_i, then the average growth rate $\bar{r}$ can be obtained from the following relation:

$$\prod_{i=1}^{N-1}(1+r_i)=(1+\bar{r})^{N-1}. \qquad (1)$$

Second, we define a period of recession (expansion) in a given country as consecutive time intervals in which growth rates are less (more) than its average growth rate, differing from the one adopted by Ausloos and Ormerod *et al.* [8,11], and record the length of each recession (expansion) period. For illustration, the differences between actual growth rates and the average one during 1955–2009 of US are presented in fig. 1(a), from which we can see the alternations of recessions and expansions.

Third, we estimate the size of a recession (expansion) by the absolute value of the difference between the average growth rate in the given period and the overall average one. For a recession period lasting M quarters, its size r^- can be derived from the following formula:

$$\prod_{i=1}^{M}(1+r_i)=(1+\bar{r}-r^-)^M. \qquad (2)$$

While for an expansion period lasting L quarters, its size r^+ satisfies the following relation:

$$\prod_{i=1}^{L}(1+r_i)=(1+\bar{r}+r^+)^L. \qquad (3)$$

If economic fluctuations of all countries are governed by the common dynamics, then they would have the same statistical characteristics. We tested the null hypothesis that the distributions are the same by pooling data of all individual countries and comparing them with that of each country [15]. The results of Kolmogorov-Smirnov tests are shown in table 1, which indicate the null hypothesis cannot be rejected at 0.01 level. Then we performed the statistical analysis on pooled data and displayed the distributions of recession and expansion periods for OECD as solid dots in fig. 2(a) and (b), respectively. It is found that the top six points of recessions (expansions) can be fitted by a power law with an exponent of -1.9601 ± 0.0237 (-1.9216 ± 0.0234). The two exponents are estimated with maximum-likelihood method [16]. It is worth noting that in terms of the cumulative size of all recession (expansion) periods, the top six points in both fig. 2(a) and (b) cover over 90 per cent of the data.

[1]Quarterly data does not exist for all OECD countries over the entire period.

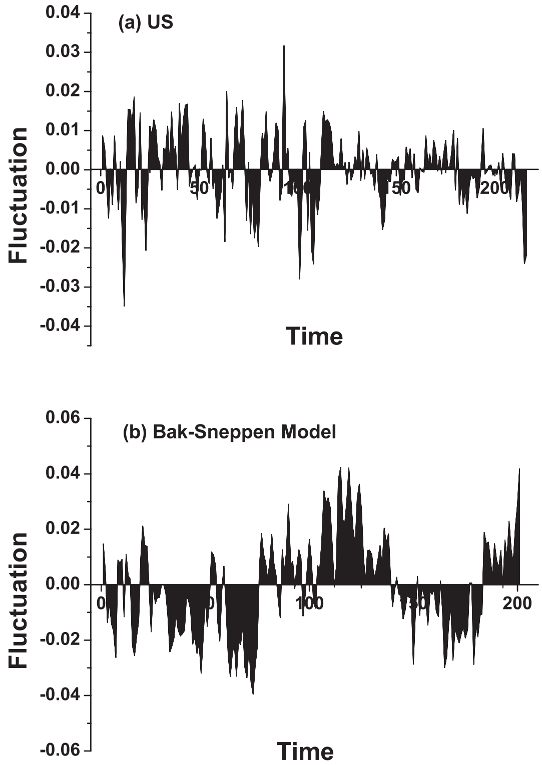

Fig. 1: (a) The differences between actual growth rates and the average one during 1955–2009 of US. (b) The differences between actual growth rates and the average one from the model.

Similarly, the sizes of recessions (expansions) of all countries are pooled and aligned as shown in fig. 3(a). The intermittent presence of events with very large size implies that it may have a distribution with a heavy tail. The statistical distributions of size of recession and expansion are presented as solid dots in fig. 4(a) and (b), respectively. It can be found that the tails of both distributions indeed follow a power law. The corresponding exponents for recession and expansion are estimated to be -3.2527 ± 0.1879 and -2.8835 ± 0.1137, respectively.

The model and the results. – To approach the underlying dynamics producing these statistical patterns,

Table 1: p-values given by Kolmogorov-Smirnov tests between the data of each country and pooled data of all individual countries.

Country	Recession period	Expansion period	Expansion size	Recession size
Australia	0.878	0.512	0.668	0.737
Austria	0.962	0.761	0.042	0.234
Belgium	0.016	0.875	0.003	0.173
Canada	0.903	0.2	0.147	0.122
Czech	0.833	0.675	0.577	0.622
Denmark	0.056	0.605	0.194	0.004
Finland	0.02	0.556	0.842	0.844
France	0.23	0.62	0.009	0.001
Germany	0.954	0.53	0.477	0.899
Greece	0.069	0.055	0	0
Hungary	0.098	0.003	0.051	0.391
Iceland	0.122	0.047	0	0
Ireland	0.021	0.003	0.747	0.561
Italy	0.586	0.919	0.124	0.031
Japan	0.649	0.749	0.009	0.116
Korea	0.571	0.911	0.169	0.666
Luxembourg	0.051	0	0.072	0.367
Mexico	0.787	0.719	0.219	0.291
Netherlands	0.182	0.685	0.758	0.558
New Zealand	0.654	0.576	0	0
Norway	0.644	0.021	0.065	0.303
Poland	0.818	0.541	0.033	0.465
Portugal	0.659	0.62	0.949	0.368
Slovak	0.414	0.391	0.159	0.176
Spain	0.637	0.437	0.149	0.479
Sweden	0.376	0.567	0.553	0.074
Switzerland	0.161	0.657	0.931	0.097
Turkey	0.688	0.023	0.001	0.112
UK	0.253	0.405	0.034	0
US	0.843	0.974	0.035	0.036

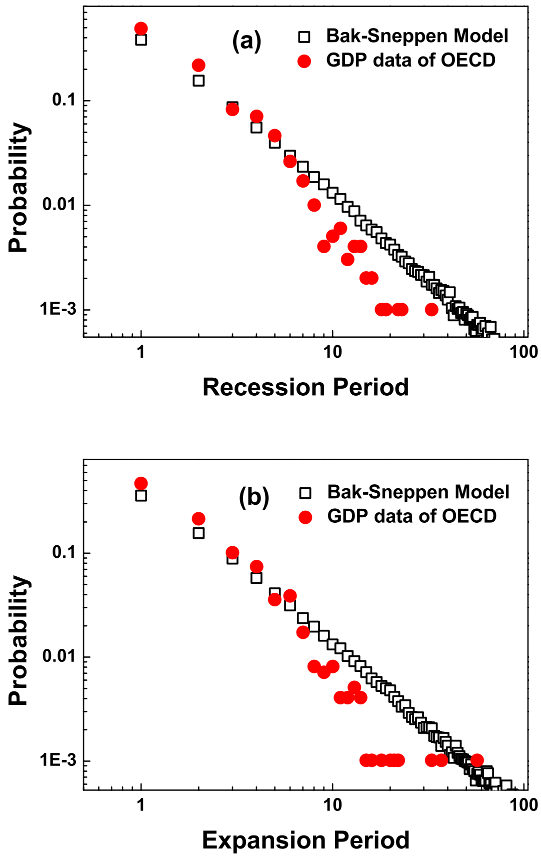

Fig. 2: (Colour on-line) Comparisons between empirical facts and the model. (a) Statistical distributions of recession periods for OECD and the model. (b) Statistical distributions of expansion periods for OECD and the model.

we concentrate on the structural changes of an economy. Schumpeter, for example, regarded technological change as a major feature of the capitalist economies, writing of "gales of creative destruction" [17], building on the tradition established by Marx [18].

Generally, an economy consists of many interactive industries. With different organizational and/or technological levels, the industries differ in performance of productivity. Assume that the industry with the lowest productivity introduces an innovation to increase its chances of survival. Consequently, some other industries that are most closely connected to it have to make an adaptive adjustment as a response to that innovation. These cascading changes will accumulate and result in a variation of aggregate behavior. So the economic fluctuations can be regarded as the outcome of consecutive occurrences of industrial innovation.

The above-mentioned scenario is what happens in the Bak-Sneppen model. So we examine how far a two-dimensional Bak-Sneppen model can reproduce the statistical patterns of empirical observations on GDP data. The model is constructed as follows. The economy consists of $K \times K$ industries. Each industry is characterized by a fitness to represent its productivity. The performance of the whole economy is signified by the average of fitness over all the industries. These industries are arranged on a two-dimensional lattice with periodic boundary conditions, where the interaction is bound to adjacent neighbors. Initially, a random number is assigned to each industry to represent its fitness. The economy evolves in a discrete time.

At each time step, we assign a new random number to the industry with the lowest fitness. In general, because it is the industry with the lowest fitness which is assigned this new level of fitness, the fitness of the industry will be increased by the innovation. Simultaneously, its four nearest neighbors will get new random numbers correspondingly as well, to allow for the fact that the generally positive innovation will impact on the fitness of these neighbouring agents. In the case of a given neighbour, however, the new fitness level will in general be equally likely to reduce its fitness as it is to increase it. The innovation itself in general has a positive impact on

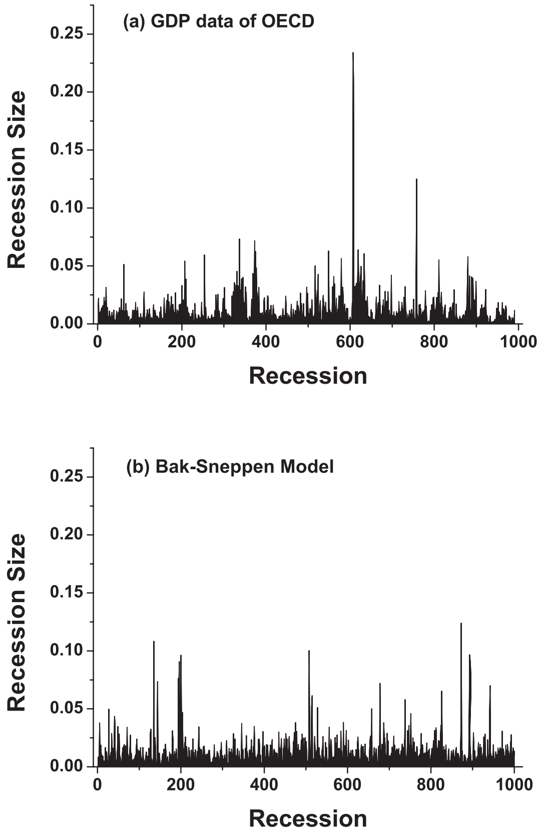

Fig. 3: (a) Recession sizes for OECD. (b) Recession sizes from the model.

the industry which introduces it, and any negative impact arises from its effect on the ability of similar industry to compete with it.

Assuming that the economic growth rate is proportional to the mean fitness of all the industries, we have an expression of growth rate g_t of the whole economy at time t,

$$g_t = \frac{\alpha}{K^2} \sum_{i=1}^{K^2} f_{it} - \beta, \tag{4}$$

where f_{it} denotes the fitness of the i-th industry at the t-th time step and α, β the coefficients. With the simulation on this iterative procedure, we can obtain a time series of economic growth rate.

Considering that the total number of US industries with four-digit NAICS Code is 1092, we set $K = 40$. The initial industrial fitness is set to be a random number between 0 and 1. In fact, the type of this distribution has no impact on the statistical property. Computer simulations with various settings of parameters α and β are performed. A well fitted result with $\alpha = 22$ and $\beta = 14.5$ is presented here. As shown in fig. 2, both the recession and expansion periods follow a power law with the exponents -1.7621 ± 0.0143 and 1.7840 ± 0.0054, respectively. It can be seen that the top six points from the model are in close agreement with those from OECD dataset.

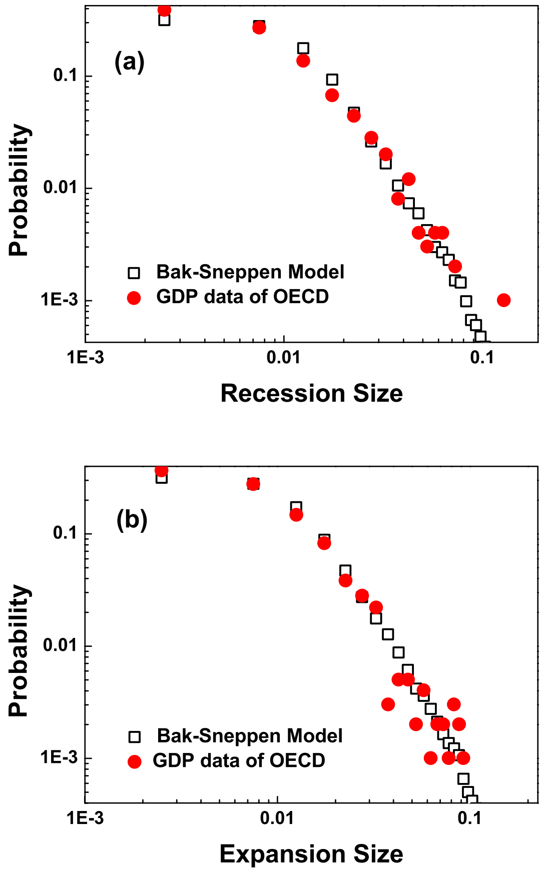

Fig. 4: (Colour on-line) Comparisons between empirical facts and the model. (a) Statistical distributions of recession sizes for OECD and the model. (b) Statistical distributions of expansion sizes for OECD and the model.

Anderson-Darling tests are carried out [19], and give p-values of 0.06431 and 0.01615, respectively. Both recession and expansion sizes have a power-law tail with the exponents -2.9919 ± 0.0354 and -3.2159 ± 0.0535, respectively. These results are shown in fig. 4. The results from the model are coincident with those from OECD dataset. Their p-values are 0.02958 and 0.12371, respectively, when the top points in fig. 4(a) and (b) are excluded.

Conclusion. – In this paper, we examine the hypothesis that innovations are a major cause of fluctuations in the growth rates of developed economies. We set up a simple model, based formally on the two-dimensional Bak-Sneppen model and with a background in economics which derives from Marx and Schumpeter, and show that it is capable of generating data which is similar to that which is observed empirically in quarterly real GDP data in the OECD economies. Whilst obviously this is not the only cause of business cycles, the results suggest that it is an important factor to consider.

* * *

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