Economic Complexity and Equilibrium Illusion

The Principle of Large Numbers indicates that macro fluctuations have weak microfoundations; persistent business cycles and interrupted technologies can be better characterized by macro vitality and meso foundations. Economic growth is limited by market extent and ecological constraints. The trade-off between stability and complexity is the foundation of cultural diversity and mixed economies. The new science of complexity sheds light on the sources of economic instability and complexity.

This book consists of the major work of Professor Ping Chen, a pioneer in studying economic chaos and economic complexity. The chapters are selected from works completed since 1987, including original research on the evolutionary dynamics of the division of labor, empirical and theoretical studies of economic chaos, and stochastic models of collective behavior. Offering a new perspective on market instability and the changing world order, the basic pillars in equilibrium economics are challenged by solid evidence of economic complexity and time asymmetry, including Friedman's theory of exogenous money and efficient market, the Frisch model of noise-driven cycles, the Lucas model of microfoundations and rational expectations, the Black–Scholes model of option pricing, and the Coase theory of transaction costs.

Throughout, a general framework based on complex evolutionary economics is developed, which integrates different insights from Smith, Malthus, Marx, Hayek, Schumpeter, and Keynes and offers a new understanding of the evolutionary history of division of labor. This book will be of interest to postgraduates and researchers in Economics, including macroeconomics, financial economics, advanced econometrics and economic methodology.

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Economic Complexity and Equilibrium Illusion

Essays on market instability and macro vitality

Ping Chen

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A spurious doctrine, but a mysterious success[1]

The great tragedy of Science – the slaying of a beautiful hypothesis by an ugly fact.

(Thomas H. Huxley, English evolutionary biologist (1870))

There's none so blind as they won't see.

(Jonathan Swift, Irish author 1667–1745 (1927))

12.1 Introduction

A central issue in business-cycle theory is the nature and origin of persistent business cycles. There are mainly two lines of economic thinking: the endogenous school and the exogenous school (Zarnowitz 1992). Schumpeter considered business cycles as the life rhythm of an economic organism (1939). Goodwin introduced the nonlinear and chaotic oscillator to describe persistent business cycles (1951, 1990). However, early evidence of economic chaos has received little interest in mainstream economics, because the existence of economic chaos may imply serious challenges to the foundations of equilibrium theory and parametric econometrics (Barnett and Chen 1988; Chen 1988a, 1993a, 1996a, 1996b; Brock and Sayers 1988). In contrast, the exogenous school represents mainstream economics since the 1930s; whose founder was Ragnar Frisch (Kydland 1995).

Hayek realized that empirical features of business cycles were difficult to understand by equilibrium theory (Hayek 1933). However, Frisch suggested that a noise-driven damped oscillator might explain both market stability and persistent cycles, which he claimed in an informal paper in 1933 (Frisch 1933). Contrary to Frisch's belief, physicists had known since 1930 that a harmonic oscillator under Brownian motion could not produce persistent oscillations (Uhlenbeck and Ornstein 1930; Wang and Uhlenbeck 1945). Today Frisch's belief is still widely held among economists and econometricians. Indeed, it is a mystery as to why Frisch never published his promised paper, and why the first Nobel Prize in economics was awarded to an unproved and wrong idea. Re-examining the Frisch model will help us to understand the origin of equilibrium belief in economic thinking.

In this chapter, we will give a brief history of the Frisch model, and then discuss its theoretical and empirical implications. We will show that the linear deterministic model of business cycles has structural instability. The effect of external noise to a linear oscillator can be studied by the Langevin equation and the Fokker–Planck equation. We may obtain the analytical solution for a harmonic oscillator under Brownian motion. Its exponential decay in amplitude and autocorrelations indicate that white noise is not capable of producing persistent cycles. We can directly estimate the intrinsic frequency and friction coefficient from real US GDP data. We then will discuss the main implications from the Brownian motion of a harmonic oscillator, and basic problems of the linear model of business-cycle theory.

12.2 Some historical notes on the Frisch model of business cycles

The Frisch model of business cycles has been a dominating influence in business-cycle theory since the 1930s. In an informal conference paper in 1933, Frisch suggested that the stable property of a market economy could be described by a damped oscillator, and that persistent business cycles could be maintained by persistent shocks (Frisch 1933). He said (the italics and bold are added by the author):

> When an economic system gives rise to oscillations, these will most frequently be damped. But in reality the cycles we have occasion to observe are generally not damped. *How can the maintenance of the swings be explained?*
>
> One way which I believe is particularly fruitful and promising is to study what would become of the solution of *a determinate dynamic system if it were* ***exposed to a stream of erratic shocks*** *that constantly upsets the continuous evolution, and by so doing introduces into the system* ***the energy necessary to maintain the swings***...
>
> I shall offer some remarks on these questions. *For a more detailed mathematical analysis the reader is referred to* ***a paper to appear*** *in one of the early numbers of* ***Econometrica***.

Readers should be aware that the above statement is an explicit design of perpetual motion machine of the second kind, which could convert random (heat) energy from environment fluctuations into mechanic work by overcoming friction force. This machine violates the second law of thermodynamics.

After a detailed discussion on the propagation problem of damped oscillators and an intuitive discussion on the impulse problem of noise impacts, Frisch declared:

> *It is reasonable to speak of an average period and an average amplitude.* In other words, there is created just the kind of curves which we know from

> actual statistical observation. I shall not attempt to give any ***formal proof****, together with* ***extensive numerical computations****, will be given in the above mentioned paper* ***to appear in Econometrica****.*

The following title did appear in *Econometrica* three times under the category "Papers to Appear in Early Issues: … Ragnar Frisch: Changing Harmonics Studied from the Point of View of Linear Operators and Erratic Shocks."

The statement appeared in Volume 1 of *Econometrica*, including Issue No. 2 (April 1933), page 234; Issue No. 3 (July 1933), page 336; and Issue No. 4 (October 1933), page 448; but it disappeared from Volume 2, Issue No. 1 (January 1934). The promised paper never did appear. This incident could have happened because Frisch himself was the editor of the newly established flagship journal for the Econometric Society.

Thirty-six years later, Frisch shared the first Nobel Prize in economics for his work in business-cycle theory. In October 1969, Professor Erik Lundberg made the following statement on behalf of the Royal Swedish Academy of Sciences (the italics are added by the author):

> *Professor Frisch's pioneer work in the early thirties involving a dynamic formulation of the theory of cycles*. He demonstrated how a dynamic system with difference and differential equations for investment and consumption expenditure, with certain monetary restrictions, produced *a damped wave movement* with wavelengths of four years and eight years. *By exposing the system to random disruptions, he could demonstrate also how these wave movements became permanent and uneven in a rather realistic manner.* ***Frisch was before his time*** *in the building of mathematical models*, and he had many successors. The same is true of his contribution to methods for the statistical testing of hypotheses.
>
> (Lundberg 1969)

In his speech delivered in Stockholm in June 1970, Frisch talked at length on everything from alchemy to particle physics, but never mentioned his prize-winning model of business cycles (Frisch 1981). From the above facts, we can speculate that Frisch quietly abandoned his model as early as 1934 but never made his view public.

Lundberg was wrong when he declared that "Frisch was before his time." In fact, physicists solved the problem of the harmonic oscillator under Brownian motion in 1930 and refined in 1940s (Uhlenbeck and Ornstein 1930; Chandrasekhar 1943; Wang and Uhlenbeck 1945). The classical works on Brownian motion were well known among mathematicians through the influential book on stochastic process (Wax 1954). All these physicists reached the same conclusion that Brownian motion was not capable of maintaining persistent harmonic cycles. Since 1963, the discoveries of deterministic chaos further indicate that only the nonlinear oscillator is capable of generating persistent cycles (Lorenz 1963; Hao 1990).

It was a great mystery why the economic community has for more than six decades ignored these fundamental results in stochastic process and adhered to the mistaken belief of noise-driven persistent cycles. It is not difficult to see why damped harmonic cycles cannot be maintained by external shocks.

12.3 Structural instability of linear deterministic cycles

Frisch was quite aware of the limitation of linear cycles (Goodwin 1993). It is known that simple harmonic cycles can be generated by a second-order linear differential equation or difference equation. However, periodic cycles exist only when friction is zero. Any deviation in parameter space may change a harmonic cycle into damped or explosive oscillation. This phenomenon is called structural instability in mathematical modeling.

12.3.1 Samuelson model in discrete time

A typical example of linear cycle is the Samuelson model of multiplier-accelerator (Samuelson 1939). The original version of the Samuelson model is in discrete-time:

$$C_t = aY_{t-1}$$

$$I_t = b(C_t - C_{t-1})$$

$$Y_t = C_t + I_t + E$$

Where $0 < a < 1$, and $b > 0$, C is consumption; I, investment; E, government expenditure; and Y is income. We have a second-order difference equation:

$$Y_t - a(1+b)Y_{t-1} + abY_{t-2} = E$$

Its solution is

$$Y_t = \frac{E}{1-a} + c_1(\lambda_1)^t + c_2(\lambda_2)^t$$

where λ_1 and λ_2 are two roots of the characteristic equation

$$A(\lambda) = \lambda^2 - a(1+b)\lambda + ab = 0$$

Its discriminant is

$$\Delta = a^2(1+b)^2 - 4ab$$

$$a = \frac{4b}{(1+b)^2} \qquad \text{when } \Delta = 0 \tag{12.1a}$$

We have oscillation solutions when $\Delta < 0$.

The condition for a periodic solution is

$$ab = 1 \tag{12.1b}$$

From economic consideration, we must have

$$0 < a < 1, \text{ and } b > 0 \tag{12.1c}$$

The equations (12.1a, b, and c) consist of main boundaries of pattern regimes. The model has four types of solutions: (i) damped oscillation regime DO; (ii) explosive oscillation regime EO; (iii) monotonically converging regime MC; (iv) monotonically increasing regime MI. Periodic oscillation regime PO occurs only at the borderline between DO and EO regimes. Patterns in the parameter space are shown in Figure 12.1. As we said before, the periodic oscillation PO is only marginally stable in the parameter space.

12.3.2 Samuelson model in continuous time

The continuous-time model of business cycles was also studied in economics (Scarfe 1977). Here, we discuss the continuous-time version of the above Samuelson model to demonstrate the relation between discrete-time and continuous-time linear models. We simply replace the difference by the derivative in the Samuelson model. We have:

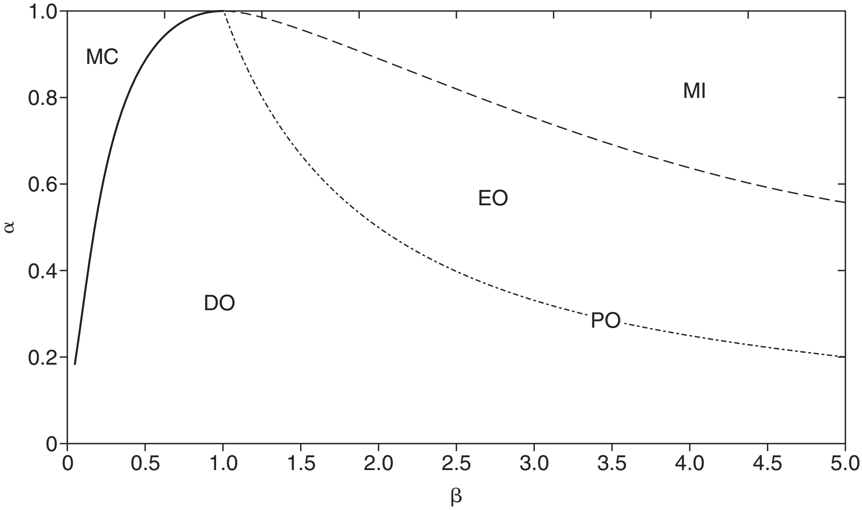

Figure 12.1 Pattern regimes of the discrete-time Samuelson model in parameter space.

Notes

MC stands for monotonic converging; DO, damped oscillation; PO, periodic oscillation; EO, explosive oscillation; MI, monotonic increasing.

$$C(t) = a[Y(t) - Y'(t)]$$

$$I(t) = ab[Y'(t) - Y''(t)]$$

$$Y(t) = C(t) + I(t) + E$$

We have a second-order differential equation

$$Y''(t) + \frac{1-b}{b} Y'(t) + \frac{1-a}{ab} Y(t) = E$$

$$Y(t) = \frac{ab}{1-a} E + c_1 e^{\lambda_1 t} + c_2 e^{\lambda_2 t}$$

where λ_1 and λ_2 are two roots of the characteristic equation (12.2)

$$\mathrm{A}(\lambda) = \lambda^2 - \frac{1-b}{b}\lambda + \frac{1-a}{ab} = 0 \qquad (12.2)$$

When $\lambda_1 = \lambda_2 = \lambda$, we have

$$Y(t) = \frac{ab}{1-a} E + (c_1 + c_2 t) e^{\lambda t}$$

We have a periodic solution only when $b = 1$. Similarly, this continuous-time model also has four dynamic regimes. Its pattern regimes are shown in Figure 12.2. Compared with the discrete-time Samuelson model, the only difference is the changing of the periodic border. The periodic oscillation is still marginally stable in the parameter space.

12.4 Brownian motion for a harmonic oscillator

The Frisch model in economics is studied as the Brownian motion of a harmonic oscillator in physics. In his 1933 paper, Frisch only discussed a damped oscillator in terms of the following equation:

$$\frac{d^2 x(t)}{dt^2} + \kappa \frac{dx(t)}{dt} + \omega^2 x(t) = 0$$

Frisch knew that this equation could produce a damped oscillation with angular frequency ω when the friction coefficient κ was not zero. By adding a series of random shocks, the Frisch model would become the Brownian motion of a harmonic oscillator, which was a natural extension of the Brownian motion of a free particle. The question is whether Brownian motion can maintain the persistent oscillation of a harmonic oscillator.

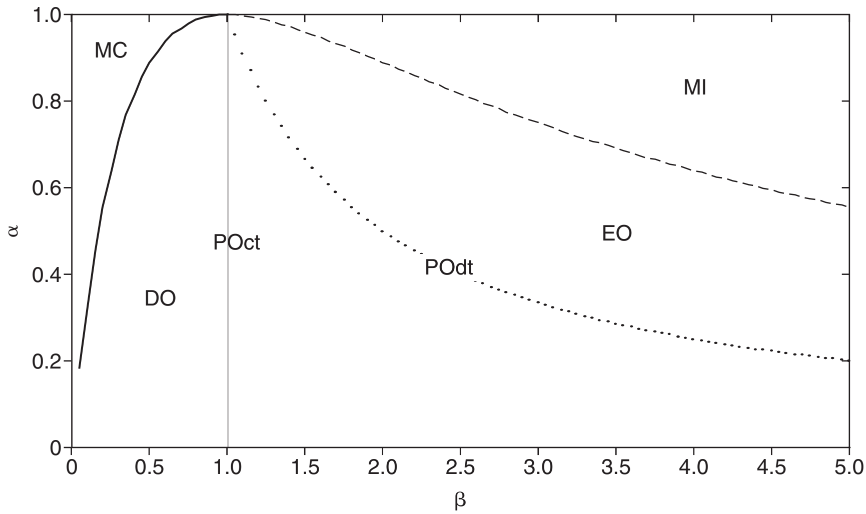

Figure 12.2 Pattern regimes of the continuous-time Samuelson model in parameter space.

Note
The periodic boundary shifts from POdt to POct.

The theory of Brownian motion for a free particle was solved by Einstein in 1905 (Einstein, 1926 for English translation). The Brownian motion theory of a harmonically bound particle was solved in 1930 and refined in the 1940s (Uhlenbeck and Ornstein 1930; Chandrasekhar 1943; Wang and Uhlenbeck 1945). Their main finding was that the harmonic particle would produce a damped harmonic oscillation under random shocks. We introduce the Langevin equation and the corresponding Fokker–Planck equation to address this issue.

The movement of a harmonic particle can be described by the following equation:

$$\frac{d^2x(t)}{dt^2} + \kappa\frac{dx(t)}{dt} + \omega^2 x(t) = \Xi(t)$$

$$< \Xi(t_1)\Xi(t_2) >= 2\Gamma\delta(t_1 - t_2) \quad \text{where} \quad 2\Gamma = \sigma^2$$

Where $x(t)$ is the coordinate,

$$\frac{dx(t)}{dt}$$

is the velocity of the particle, and $\Xi(t)$ is a continuous-time Gaussian white noise with zero mean and standard deviation of σ, Γ is diffusion coefficient, and κ is friction coefficient.

The Langevin equation can be transformed into a Fokker–Planck equation:

$$\frac{\partial P(x,v,t)}{\partial t} = -v\frac{\partial P(x,v,t)}{\partial x}$$

$$+\frac{\partial}{\partial v}[(\kappa v+\omega^2 x)P(x,v,t)]+\Gamma\frac{\partial^2 P(x,v,t)}{\partial v^2}$$

$$v=\frac{dx}{dt}$$

$$P(x,v,0)=\delta(x-x_0)\delta(v-v_0)$$

This equation can be analytically solved. We can calculate its average displacement and correlations. We have

$$<x>=\frac{v_0}{\omega_1}\exp\left(-\frac{\kappa t}{2}\right)\sin(\omega_1 t)$$

$$+\frac{x_0}{\omega_1}\exp\left(-\frac{\kappa t}{2}\right)\left[\omega_1\cos(\omega_1 t)+\frac{\kappa}{2}\sin(\omega_1 t)\right]$$

$$\Rightarrow 0 \quad \text{when } t\to\infty$$

Where angular frequency ω and frequency f are associated by $\omega = 2\pi f$, the intrinsic angular frequency ω can be obtained from the characteristic equation. For the realized angular frequency ω_1, we have:

$$\omega_1^2=\omega^2-\frac{\kappa^2}{4}$$

We can calculate the mean square displacement of the harmonic particle (Wang and Uhlenbeck 1945):

$$<(x-<x>)^2>=\frac{\Gamma}{\kappa\omega^2}$$

$$-\frac{\Gamma}{\kappa\omega^2}\frac{1}{\omega_1^2}\exp\left(-\frac{\kappa t}{2}\right)\left[\omega_1^2+\frac{\kappa^2}{2}\sin^2(\omega_1 t)+\frac{\kappa\omega_1}{2}\sin(2\omega_1 t)\right]$$

$$\Rightarrow\frac{\Gamma}{\kappa\omega^2} \quad \text{when } t\to\infty$$

$$<x(t)x(t+\tau)>=\frac{\Gamma}{\kappa\omega^2}\exp\left(-\frac{\kappa t}{2}\right)\left[\cos(\omega_1\tau)+\frac{\kappa}{2\omega_1}\sin(\omega_1\tau)\right] \qquad (12.3)$$

Here, τ is the time delay.

From Einstein, we know the Brownian motion of a free particle has a different result (Einstein 1926):

$$< s^2 >= 2\Gamma t \tag{12.4}$$

Both of the equations (12.3) and (12.4) were verified by experiments (Barnes and Silverman 1934). We can see then that a harmonic oscillator under the Brownian motion does not lead to a diffusion process. Its oscillation will have become rapidly damped into residual fluctuations without apparent periodic motion.

12.5 US business cycles as Brownian motion of a harmonic oscillator

The main features of a damped oscillation under Brownian motion can be estimated from its autocorrelations (Wang and Uhlenbeck 1945):

$$\rho(\tau) = \exp\left(-\frac{\kappa\tau}{2}\right)\left[\cos(\omega_1\tau) + \frac{\kappa}{2\omega_1}\sin(\omega_1\tau)\right]$$

The autocorrelations of displacement show damped oscillations with an exponential decay. We can define a relaxation time T_κ

$$T_\kappa = \frac{2}{\kappa}$$

We can see that the realized oscillating frequency is determined by the free intrinsic frequency and the friction coefficient. We can directly measure κ and ω_1 from the autocorrelations of empirical data. The noise-driven damped oscillator produces only short temporary cycles, whose life is in the order of T_κ. The realized harmonic frequency f_1 can be measured by the first zero point in autocorrelation:

$$\omega_1 = \frac{2\pi}{T_{ac}} \text{ and } T_{ac} = 4To,$$

$$\omega^2 = \omega_1^2 + \frac{\kappa^2}{4}$$

Because autocorrelations are a measure of a stationary process, we must choose the proper way to remove growth trends from the empirical time series. The choice of detrending represents a choice in the observation reference (Chen 1996a, 1996b). The first difference (FD) detrending in econometric analysis represents the smallest time window and a whitening filter. The log-linear detrending (LLD) represents the largest time window that covers a whole historical period. The Hodrick–Prescott (HP) filter defines a nonlinear smooth trend with a media time window (Hodrick and Prescott 1997; Kydland and Prescott 1982).

We can define a gain factor G that is the ratio of the residual variance to the noise variance:

$$G = \frac{< x^2 >}{\sigma^2} = \frac{2}{\kappa\omega^2}$$

From US Real GDP Quarterly Data (1947–1992), we have the following results in Table 12.1. Because the autocorrelations of the real GDP quarterly series are rapidly damped within only one or two cycles, so the errors of estimation are quite large. However, the magnitudes of these parameters are still reasonable to accept. Some qualitative features can be seen from the Table 12.1.

First, the harmonic oscillator will quickly cease its harmonic oscillation within one or two cycles, ranging from two to 40 years depending on your observation reference of business cycles. The relaxation time T_κ is the shortest for FD but the longest for LD. Clearly, random shocks cannot maintain persistent cycles of a damped oscillator.

Second, different time windows reveal different pictures of business cycles. The FD series has the smallest variance and the shortest period, while the LD cycle has the largest variance and the longest period. The variance and period of the HP cycles are between the FDs and LDs. Among them, only the FD filter has a damping effect to external noise. Both HP and LD filters have an amplifying effect to external noise. These features add additional difficulty to the choice of one's reference system in equilibrium economics.

Table 12.1 The Frisch model for US Real GDP cycles (time unit is year)

	κ	ω	ω_I	T	T_I	T_κ	σ	G
FDs	1.02	1.86	1.79	3.4	3.5	2.0	0.010	0.57
HPc	0.41	1.32	1.30	4.7	4.8	4.9	0.018	2.8
LDc	0.055	0.15	0.11	42.0	57.0	36.0	0.021	1600

Source: Federal Reserve Bank at St. Louis.

Notes
Where κ is the friction coefficient,
ω the angular frequency,
ω_1 the realized angular frequency,

$$T_1 = \frac{2\pi}{\omega_1}$$

the observed period,

$$T = \frac{2\pi}{\omega_1}$$

the intrinsic period, T_κ the relaxation time, σ the standard deviation, G the gain factor.

From the above features, we can see that the equilibrium perspective does not provide a unified approach in empirical analysis. Neo-classic growth theory implies the LD approach in economic growth (Solow 1956). Friedman preferred the FD to the LD approach because the LD introduces boundary dependence (1969). FD detrending is widely used in econometrics and financial analysis because of its white appearance. The problem of the FD approach is that it is hard to identify an external source of business cycles, which needs to be larger than the US economy!

12.6 Conclusion

The Frisch model of business cycles is not capable of understanding persistent cycles observed in market economies. Random walks cannot deliver sufficient energy to overcome friction because of the second law of thermodynamics. From Slutsky to Frisch, the nonlinear nature of persistent business cycles has been obscured by the mistaken belief in noise-driven business cycles (Slutsky 1937).

Certainly, the Frisch conjecture did raise many interesting questions about the impact of external noise on deterministic oscillators. So far as we know, persistent cycles can only be generated by nonlinear dynamical systems, such as limit cycle solution of the van der Pol model and chaos trajectory of the Rössler model (1976). External noise may change the stability pattern of a nonlinear oscillator when the noise level goes beyond some threshold (Chen 1987b).

It was a great mystery how a Nobel Prize was awarded to a false claim without theoretical analysis and empirical evidence. Scholars of the history of science may be interested in further questions, such as why Frisch gave up his promised paper and why he kept his silence about his model since 1934.

From our experience in studies of economic chaos, the main obstacle to the nonlinear and nonequilibrium perspective is some spurious doctrine in equilibrium thinking, such as the Frisch model. The wishful thinking of the Frisch model is quite similar to perpetual motion machine in the history of thermodynamics. Schumpeter considered business cycles like the heart beat, which was the essence of the organism (Schumpeter 1939). According to nonequilibrium thermodynamics, biological clock can only emerge in dissipative systems with energy flow, information flow, and matter flow (Prigogine 1980). Therefore, nonequilibrium mechanism is the nature of economic evolution, and nonlinear dynamics is the origin of business cycles. The one valuable lesson gained from the mystery surrounding the Frisch model is that an interdisciplinary dialogue between economists and other scientists would be fruitful for the science community.

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Notes

Preface

1 Paul A. Samuelson passed away on December 13, 2009. We lost a great mind, who was not only a founder of mathematical economics and neo-classic synthesis in the 1940s, but also an early supporter of studies in economic chaos. We are unfortunate not to have him reading our book before publication. We can still share his insights on the future development of economics after this crisis.

Few economists know that Samuelson himself developed a chaos model in micro utility theory (1986, 1990). But his strong interest in empirical evidence of economic chaos was more visible from his letters to the author dated June 8, 1987 and December 22, 1987, in which Samuelson showed cautious interest in our early work on monetary chaos and raised the issue of how to distinguish deterministic chaos with other candidates such as fractal and Pareto-Levy distributions. He kindly offered his advice to the younger generation of economists, when he said: "My various remarks should not throw cold water on your pioneering efforts. However, there is a role for tough mindedness and self-criticism along with a role for daring in science." After we found wide evidence of color chaos from macro and stock indexes, Samuelson asked the author if we could develop a more general framework so that neo-classical models could be integrated as special cases in a general nonlinear theory. This is a grand task, once Keynes aimed to parallel Einstein's approach in his general theory (Galbraith 1994).

Samuelson's foresight was his keen sense of paradigm shift in economic science, which was revealed by his letter to Dr. Linda Reichl, the acting director for the Ilya Prigogine Center for Statistical Mechanics and Complex Systems at University of Texas at Austin, dated September 20, 1995, for evaluation of Ping Chen's work for academic promotion. After his positive evaluation, his letter made a further remark:

> What cannot be predicted at this time is whether one or another of his innovative paradigms will turn out to be of great moment to the corps of leading mainstream economists. He is in the queue of promising researches but whether his lottery ticket contains a winning number – only the future can tell.

Honestly speaking, we were still worried about possible applications of economic chaos when Samuelson already considered the issue of innovative paradigm. We realized the need of paradigm change after the Asian financial crisis and transition depression in EEFSU (see Chapter 2).

In his last interview on June 17, 2009, Samuelson once more emphasized the lesson for economists from the Great Depression: "That was a disequilibrium system. I realized that the ordinary old-fashioned Euclidean geometry didn't apply" (Clark 2009).

I wish that our younger readers could continue the cause pioneered by Keynes to develop a general theory of nonlinear nonequilibrium economic dynamics, so that we could better understand the viable nature of the market and the proper role of governments and society as integrated parts of the modern mixed economy.

This note was added by Ping Chen on December 19, 2009 in memory of Paul Samuelson.

2 Equilibrium illusion, economic complexity, and evolutionary foundation in economic analysis

1 Originally published in (2008) *Evolutionary and Institutional Economic Review*, 5(1), 81–127 (Japan).
2 In Chapter 16, the relative deviation is renamed as market variability (MV) as a feature measurement of market stability.

3 Evolutionary economic dynamics: persistent cycles, disruptive technology, and the trade-off between stability and complexity

1 This is the chapter 15 in Kurt Dopfer edited, *The Evolutionary Foundations of Economics*, pp. 472–505, Cambridge University Press, Cambridge (2005).
2 Edward Prescott told the author at the AEA2001 meeting that the HP filter was first used by John von Neumann.
3 This ratio is called the coefficient of variation (CV) in statistics and unitized risk in finance literature. We call it the relative deviation with a comparison when we consider the standard deviation as the absolute deviation. This term makes a sense from physics perspective. Later in Chapter 16 section 16.5, we rename it as the market variability (MV). MV is a better macro indicator since it is more stable than the conventional measure of variance in asset pricing theory.
4 "Work" is a physics term, which means the amount of "effective energy" transferred into "mechanical work" measured by the "acting force" times the "traveling distance." In contrast, the "wasted energy" measured by the "heat" energy or "transaction cost" in economics term.
5 The uncertainty principle in quantum mechanics implies that the minimum amount of energy is needed for getting information on particle's speed and position, or time and energy (Brillouin 1962). In this regard, the concepts of perfect information and rational expectation in macro dynamics are against the uncertainty principle in quantum mechanics. Therefore, the so-called rational expectations demand infinite information without costing infinite energy. This scenario is impossible in a realistic physics world. In order to develop an empirical science of economics, we need a general theory, which is consistent with laws of physics and constraints in ecology and biology.

4 Empirical and theoretical evidence of economic chaos

1 Originally published in (1988) *System Dynamics Review*, 4(1–2): 81–108.
2 After the publication of this article, we were informed by economists that there was a fundamental debate between Austrian school and monetarist school. Austrian school believed that monetary movements were endogenous in nature, while monetarists claimed that monetary movements are exogenous. Interesting readers could study the writings by Friedrich Hayek (1933) and Milton Friedman. Monetarists relied on their analysis on statistics based on linear regression analysis. Austrians thought that simple (linear) mathematics was not capable of understanding social phenomena. We found out that new tools of nonlinear dynamics could address the old debate on the nature of business cycles. It turned out that our discovery of monetary chaos is an evidence of endogenous monetary cycles and our model of soft-bouncing oscillator is capable of understanding sources of endogenous business cycles.

5 Searching for economic chaos: a challenge to econometric practice and nonlinear tests

1 In Richard Day and Ping Chen (Eds.) (1993) *Nonlinear Dynamics and Evolutionary Economics*, Chapter 15, pp. 217–53, Oxford: Oxford University Press.

6 A random walk or color chaos on the Stock Market? Time–frequency analysis of S&P indexes

1 Originally published in (1996) *Studies in Nonlinear Dynamics and Econometrics*, 1(2): 87–103.

2 The original symbol was the Greek letter λ used by the originator (Hodrick and Prescott 1997). We use the Latin letter s for the smoothing parameter to avoid confusion with the symbol of Lyapunov exponent λ in our writing. The HP filter was previously studied by Italian astronomer Schiaparelli in 1867 (Stigler 1978) and Hungarian mathematician and physicist von Neuman in the ballistic literature (von Neuman *et al.* 1941).

3 The numerical algorithm is called the time–frequency distribution series (TFDS). The computer software is marketed by National Instruments under the commercial name of Gabor spectrogram as a tool kit in the Lab View System. We prefer to call this analytical algorithm the WGQ (Wigner–Gabor–Qian) transform in physics conversion.

7 Trends, shocks, persistent cycles in evolving economy: business-cycle measurement in time–frequency representation

1 In W.A. Barnett, A.P. Kirman, and M. Salmon (eds.) (1996) *Nonlinear Dynamics and Economics*, Chapter 13, pp. 307–31, Cambridge, Cambridge University Press.

8 Origin of division of labor and stochastic mechanism of differentiation

1 Originally published in (1987) *European Journal of Operational Research*, 30(3): 246–50.

9 Imitation, learning, and communication: central or polarized patterns in collective actions

1 Originally published in A. Babloyantz (ed.) (1991) *Self-Organization, Emerging Properties and Learning*, pp. 279–86, New York: Plenum.

10 Needham's question and China's evolution: cases of nonequilibrium social transition

1 In George P. Scott (ed.) (1990) *Time, Rhythms, and Chaos in the New Dialogue with Nature*, Chapter 11. pp. 177–98, Ames Iowa: Iowa State University Press.

11 China's challenge to economic orthodoxy: Asian reform as an evolutionary, self-organizing process

1 Originally published in (1993) *China Economic Review – An International Journal*, 4(2): 137–42.

12 The Frisch model of business cycles: a spurious doctrine, but a mysterious success

1 Originally (1999) *IC2 Working Paper* 99–05–01, University of Texas at Austin, USA; and CCER Working Paper 1999-007, China Center for Economic Research, Peking University, Beijing, China.

13 Microfoundations of macroeconomic fluctuations and the laws of probability theory: the Principle of Large Numbers vs. rational expectations arbitrage

1 Originally published in (2002) *Journal of Economic Behavior and Organization*, 49(3): 327–44. Received 8 March 1999; received in revised form 4 September 2001; accepted 6 September 2001.

2 This ratio is called variation coefficient in statistics and finance literature when the mean is positive. Mathematically speaking, this is a dimensionless number, which can be called "the relative deviation" comparing to the standard (absolute) deviation. In macroeconomic analysis, this ratio can be considered as a salient indicator of "market variation" in business cycles and financial volatility.

3 The pattern of

$$\frac{1}{\sqrt{N}}$$

is well known in physics and biology literature (Schrödinger 1944) under various technical terms, such as the relative magnitude of fluctuation (Reif 1964), the root-mean-square relative fluctuation about the mean (May 1974a), and the fractional deviation (Reichl 1998). The terms "relative deviation," "Principle of Large Numbers," and "positive variable" are used by the author for general readers in understanding the points at issue.

4 We made one mathematical simplification for the LMI model. Here, our allocation variable ϕ is

$$\left(\frac{\vartheta}{2}\right)$$

in the original LMI formulation. Other symbols in this section are the same as the LMI model for the reader's convenience.

14 Complexity of transaction costs and evolution of corporate governance

1 Originally published in (2007) *Kyoto Economic Review*, 76(2): 139–53.

15 Market instability and economic complexity: theoretical lessons from transition experiments

1 In Yang Yao and Linda Yueh (eds.) (2006) *Globalisation and Economic Growth in China*, Chapter 3. pp. 35–58, Singapore: World Scientific.

16 From an efficient to a viable international financial market

1 In R. Garnaut, L. Song, and W.T. Woo (eds.) (2009) *China's New Place in a World in Crisis: Economic, Geopolitical and the Environmental Dimensions*, Chapter 3. pp. 33–58, Australian National University E-Press and The Brookings Institution Press, Canberra.

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