From Complexity Science to Complexity Economics

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Abstract

The central idea of analytical science is that the whole equals the sum of its part. This reductionist view with certainty was challenged by computational uncertainty in classical mechanics and system approach in biology and thermodynamics. The interdisciplinary science of complex systems shed new lights on nonlinearity dynamics and non-equilibrium evolution. There are three lines of thinking in studying economic complexity. The first school focuses on computational uncertainty including deterministic chaos and dis-equilibrium statistical distributions. The Santa Fe school and econophysics consider economies as a fragile order at the edge of chaos. The second school developed system approach of self-organization and dissipative structure. Brussels-Austin-Shanghai school pioneered by Ilya Prigogine emphasizes the role of time arrow in living systems. Order out of chaos reveals a new kind of viable order, such as life cycle and economic resilience. The third school was more pluralistic and inclusive in economic thinking. Some essential features of psychology, behavior and culture could be modeled by advanced mathematics. Basic doctrines in neoclassical economics are inconsistent with basic laws in physics and biology. Complexity economics may accomplish the dream of Keynes. A general economic theory is capable of integrating special cases from diversified economic thoughts.

Main features of simplicity and complexity in economic thinking

There is no common definition of complexity in the emerging science of complexity (Waldrop 1992). Mathematicians and computer scientists are mainly interested in computational complexity and algorithmic complexity. For studies of economic complexity, three disciplines made important impact to economic thinking, including system theory in biology, chaos theory in physics, and network theory in mathematics.

It is easier to define what is *simplicity* in neoclassical economics and econometrics. We will compare *simplicity* vs. *complexity* in competing economic theories. A more philosophical term is *equilibrium* economics in mainstream vs. *non-equilibrium* economics or so-called heterodox economics. We list seven pairs of simplicity vs. complexity in economics concepts.

Methodological individualism vs. system & network thinking

The typical example of simplicity model in neoclassical economics is the representative agent model or Robinson Crusoe economy. Its philosophical doctrine is atomism or reductionism. Its main idea is that the whole is the sum of parts. It abstracts away all social and economic differences, such as life cycle and income inequality. In contrast, other schools of thought would consider that the whole is more than the sum of parts. These economists would introduce more complex structure and interactions in economics, such as system dynamics in management with many parts and many players (Forrester 1961), and evolutionary economics with changing structure and history, etc.

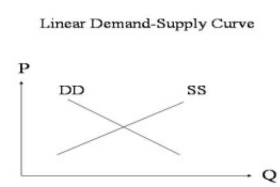
In mathematical term, methodological individualism only considers the one-body problem or two-body problem, which could be transferred into a one-body problem. One striking model in neoclassical economics is the Brownian motion model in the Black-Scholes model of option pricing. The model is a representative agent model with only one particle (Black and Scholes 1973). Theoretically, modeling competition or cooperation needs at least two parties; studying social interaction should solve the many-body problems. Neoclassical model with one representative agent could only study optimization problem without competition and division of labor. Its economic picture is essentially a pre-modern society without industrialization.

Modern examples of many-body problems are complex adaptive system (CAS) with many interacting agents and statistical mechanics model with large number of identical particles. Their behavior is more complex than neoclassical model of representative agent.

One simple implication is that homogeneous vs. non-homogeneous structure in economy. One important issue in economics is inequality. This issue is ignored by methodological individualism and the representative agent model.

Linear vs. nonlinear models, and single vs. multiple equilibriums

The basic model in neoclassical microeconomics is the linear demand and supply curves with only one equilibrium state. Its macroeconomic version is the IS-LM model. Its main feature is the single stable equilibrium state at the cross point of DD-SS curves. In contrast, the nonlinear demand and supply curves may have multiple equilibrium states. Some equilibrium states may be unstable. See Fig. 1.



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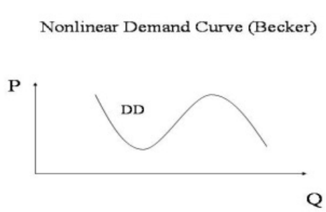

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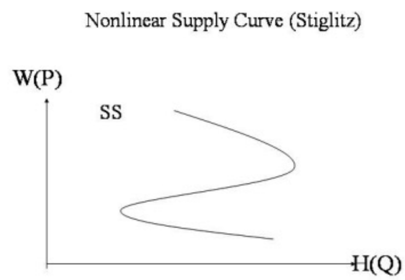


(1c)

Fig. 1. Linear and Nonlinear Demand Supply Curves in Micro.

(1a) Linear demand (DD) and supply (SS) curves with single stable equilibrium. This is a typical picture of a self-stabilized market by "invisible hand" that resulted from rational behavior in neoclassical economics.

(1b) Nonlinear S-shaped demand with social interaction (Becker 1991).

There are three equilibrium states (two stable and one unstable) corresponding to the same price. This is a picture of collective behavior often observed from fashion or stock market where irrational behavior is driven by social interactions.

(1c) Nonlinear Z-shaped labor supply curve in labor market. Surplus labor in subsistence regime (the bottom segment) and shortage labor in leisure regime (the top segment) coexist in an uneven society (Stiglitz 1976, Dessing 2002).

Equilibrium vs. nonequilibrium process, and convergence vs. diversity in economic evolution

The central idea in neoclassical economics is stability, which implies an equilibrium process or a convergent trend. In contrast, the main idea in evolutionary biology and evolutionary economics is diversity or a divergent trend.

To ensure market stability, neoclassical economics impose many conditions for theoretical modeling, including stable single equilibrium, negative feedback in dynamics, convex set in microeconomics, decreasing returns or constant returns to scale in technology, finite mean and variance in econometrics, zero transaction costs in institutional economics, random walk or Brownian motion model in finance, optimization framework in micro and macro economics, continuity and smoothness in utility and production functions, ergotic theorem in econometrics and economic statistics, path independence in economic history and institutions, nothing new under the sun, etc.

In contrast, non-equilibrium implies diversity and changes. Its mechanism includes multiple stable and unstable equilibrium states, positive feedback and instability, non-convex set, increasing returns to scale, Levy distribution, fat tail distribution, multi-humped distribution, fractal, power law, significant and varying transaction costs, birth-death process, nonlinear dynamics in open systems (without optimization in closed system), catastrophe, bifurcation, phase transition, bubbles, crisis, slow and sudden changes, self-organization, spontaneous order, emergence, path dependence in history and institution, origin and evolution of life, city, state, and organization, etc.

Among competing schools of economic thoughts, neoclassical school is the only equilibrium school. All non-orthodox schools in economics are belong to non-equilibrium perspective in various degree, including evolutionary economics, Marx economics, institutional economics, Austrian economics, Schumpeterian economics, Keynesian economics, behavioral economics, and complexity economics, etc. Even though their political orientations and mathematical formulations are quite different.

From philosophical perspective, equilibrium school has strong belief in universal value and institution, while evolutionary schools have a more inclusive view on human value and institutions. In this regards, neoclassical economics is a Newtonian paradigm while economic anthropology is a Darwinian paradigm in economic thinking.

Certainty vs. uncertainty in dynamics, and stationary vs. non-stationary time series analysis in econometrics

In econometrics and time series analysis, neoclassical economics make strong prediction with certainty. Positive economics proposed by (1953a) claimed that econometric analysis could be verified by out of sample tests, which is only possible for stationary time series without structural changes in history. Dynamic models demand stability condition of deterministic trajectory. Statistical analysis requires small residual in econometric modeling, etc.

There are similar concept in physics and mathematics. Physics terms are time symmetric (reversible) in isolated and closed systems with conservation of energy vs. time asymmetric (irreversible) dynamics in open systems without energy conservation. Mathematic terms are integrable vs. non-integrable systems. Econometric forecast is impossible with predicable certainty for non-integrable systems.

External shocks vs. endogenous cycle in business cycle theory

One unique nature in economic theory is its philosophy excludes frequency spectra in business cycle analysis. Neoclassical school prefer external shocks as the only source of business cycles because its belief in invisible hands. Econometric analysis only uses white noise models, such as random walk and Brownian motion, as driving force of business cycles. Econometrics journals do not publish time series analysis based on frequency analysis.

In contrast, frequency analysis is widely used in science, engineering, and medical industry. Classical and quantum mechanics made tremendous progress based on harmonic oscillator model. In theory, noise representation and frequency representation is equivalent in spectral analysis based on the uncertainty principle in quantum mechanics and information theory, since the pulse function is a delta function in time and frequency function is a delta function in frequency.

Neoclassical economics in macro and finance theory simply deny the possibility of internal market instability and market crisis by ruling out theoretical models of deterministic cycles. This is a clear feature of economic theology or alchemy (Hendry 1980, 2001) rather than economic science (Foley 2008).

Time-symmetric and time-asymmetric process in economies

Historian and social scientists knew history is the most complex factor in human affairs, while neoclassical economics abstract out all traces of history in economic theory. We refer history as irreversibility or time arrow in physics terms. In contrast, physics laws in closed system can be characterize symmetry in time and space. For example, the conservation law of energy is a result from time symmetry, while conservation of momentum is a result of space symmetry, light sets speed limit because of symmetry in four-dimensional space-time.

The time-symmetric features in neoclassical economics include symmetry between demand and supply in microeconomics; Markov process in economic statistics, random walk and Brownian motion in finance; AR (n) model with short correlations in time series analysis; unlimited growth in macroeconomics, and zero-transaction costs in institutional economics, and universal value in economic philosophy.

History and culture are most visible time-asymmetric features that are widely discussed in heterodox economics and social science. The idea of biological clock (Schumpeter 1939) and spontaneous order (Hayek 1991) is economic forms of self-organization and economic complexity. Nonlinear development and divergent evolution was studied in economics (Engels 1884, 1902, Rostow 1960, 1990), behavior (Thaler 2015), institution (Hodgson 2007), sociology (Weber 1930), anthropology (Harris 1978), and psychology (Piaget 1971, Buss 2019).

Homogeneous models vs. hierarchal structure

Homogenous models are prevalent in both economics and physics. However, both political economist and psychologist realize the hierarchal structure exists in human society and human behavior (Marx 1978, Maslow 1970). We found out three level structure of micro-meso-macro from empirical analysis of macro and finance index based on the Principle of Large Numbers (Chen 2002). The two level model of micro-macro structure in neoclassical economics is not sufficient to understand economic complexity from empirical data.

The origin of complexity science in physics and ecology

Three disciplines play important role in studying complexity: physics, mathematics, and ecology. They are closely related by mathematical problems in nonlinear dynamical systems. Computational complexity was started in mechanics as early as 1899 from the three-body problem such as the dynamics among sun, earth, and moon in celestial mechanics. Mathematics developed new tools in bifurcation theory and nonlinear dynamics. System theory began in biology in 1930s. Evolutionary thermodynamics and self-organization shed new lights on order and chaos. Complexity studies became interdisciplinary studies since 1970s.

There is a criticism that complexity findings are more like metaphor rather than science (Horgan 1995). We must be careful about numerical results of computer experiments and real dynamics in a real world. Interesting patterns in cellular automata may not explain simple mechanism in cell biology.

Computational uncertainty and deterministic chaos

The first motivation to study complexity began with computational uncertainty in classical mechanics.

Newton mechanics establish a deterministic worldview, where trajectory of a particle is predictable if its dynamical equations and initial conditions are known. This was the origin of scientific determinism first proposed by Laplace in 1814 (1902). A dynamical system is defined as stable, if a small deviation from the initial condition would rapidly converges to its deterministic trajectory. Mathematically speaking, the dynamical system is integrable, if its analytical solution can be expressed as a series of analytical functions and integrals. This belief was shaken by the discovery of deterministic chaos (Hao 1990).

Studies of deterministic chaos began from mathematical theory of nonlinear dynamics. Poincaré first shown that there was no analytical solution of the three-body problem in gravitation theory (1887). The butterfly effect was first studied in radar problem (Cartwright and Littlewood 1945), and later coined by Ed Lorenz, who discovered computational chaos from numerical solutions of three-dimensional nonlinear differential equations in climate dynamics (Lorenz 1963). The popular term of "chaos" was coined by mathematicians (Li and York 1975). Other models of computational chaos were found from one dimensional nonlinear difference equation i.e. logistic map (May 1976), and nonlinear delay-differential equation (Mackey and Glass 1977). Deterministic chaos has several features that are "complex" in comparison to linear dynamics, such as bifurcation mechanism with changing parameter, sensitive to initial condition characterized by positive Lyapunov exponent l, dense periodic orbits, fractal dimensions, and strange attractors. A chaotic trajectory only has limited predictability.

Experimental evidence of deterministic chaos was widely discovered from physics, chemistry, biology, and climate dynamics since 1970s.

System theory in ccology and biology

The second motivation of studying complexity was rooted in understanding of physics foundation of biology. Many scholars realize the fundamental differences between mechanic and biological phenomena. The question is how to characterize living mechanism.

The starting point is finding the alternative of reductionism. Biologist developed the framework of system theory (Bertalanffy 1934, 1968). Cybernetics introduced the concept of negative feedback as the main mechanism for self-stabilization behavior (Wienner 1948). Negative feedback becomes the central mechanism for market stability in neoclassical economics and system dynamics. Haken proposed the idea of Synergetics to characterize the holistic view of biology (1977). Complex system theory is easily accepted by management economics (Beinhocker 2006).

Three physicists made fundamental contribution in understanding biological phenomena. Schrödinger pointed out that there were two opposing features in biology: stability and variability. He proposed four ideas for describing organism, such as meta-stable state, non-periodic crystal, negative entropy, and principle of large numbers in molecule biology (Schrödinger 1948). May studied the stability of nonlinear ecological systems. He found out the large ecological systems may become less stable than simpler systems (May 1974). Prigogine's idea of self-organization and dissipative structure construct chemical reaction model of living system such as BZ reaction and division of labor in ant's behavior (Nicolis and Prigogine 1977).

Thermodynamics of evolution and self-organization in physics

Early study in bioeconomics and biophysical economics realized the important link between thermodynamics and economics (Georgescu-Roegen 1971). Some basic concepts in neo-classical economics are at odds with thermodynamics and quantum physics.

Prigogine pointed out a fundamental contradiction between thermodynamics and biological evolution (Prigogine et al, 1972). The second law of thermodynamics predicts an evolutionary trend from non-equilibrium structure to equilibrium disorder characterized by entropy, while biological evolution shows an opposite trend from simple to complex living systems. How to bridge the gap between physics and biology? Prigogine defined three systems in thermodynamics. The heat death without order is resulted from thermal equilibrium in isolated system. The equilibrium structure like static crystal can be observed from closed systems with energy exchange with environment. The dissipative structure in open system exists by constant energy flow, matter flow, and information flow. Living and social systems can only emerge in open system. Prigogine's non-equilibrium thermodynamics paves the physics foundation for living world. The fatal mistake in neoclassical economics is built upon closed system. That is why neoclassical economics is static model in nature without evolutionary change in space and time.

Time arrow is the essential feature in living system because history is irreversible in non-equilibrium process (Prigogine 1980). Neoclassical model based on equilibrium and random walk simply denies the role of history and time asymmetry in economics.

In non-equilibrium physics, "*complexity science*" or "*complex systems*" is an extension of evolutionary thinking in biology. Prigogine's idea of "Order Out of Chaos" had strong influence among biologists, and social scientists (Toffler 1980, Prigogine 1984).

A brief history of studies in economic complexity

Study of economic complexities experienced two stages. The first stage is started by mathematical complexity in economic models. The second stage is characterized by empirical studies in economic research. The third stage is developing new economic theory with economic complexity. We would give a brief outline here.

Mathematical complexity in economic modeling

Chaos was known as a new science in public media since 1980s (Gleick 1987). However, the study of economic chaos met with heavy barrier because its conflicts with theoretical framework of neoclassical economics.

The first wave of studies in economic complexity was simply applied existed math models into economic theories. The known example was 1D (one-dimensional) chaos model of logistic map (May 1976) transformed into irregular growth cycle in nonlinear difference equation (Day 1982), and 2D (two-dimensional) chaos model of Henon map (1976) into monetary theory (Benhabib 1980). The limit cycle model in nonlinear differential equation was first introduced by Goodwin (1951). The Lorenz chaos model with three-dimensional differential equations (Lorenz 1963) was introduced by Goodwin (1990). New mathematical concepts of catastrophe, bifurcation, and fractals were introduced into economic models (Rosser 1991, 2009).

Some images like “butterfly effect” and “artificial life” are mainly computer experiments without control experiment. In real climate dynamics, hurricane speed is far below light speed. A butterfly flipping its wings could not generate a real tornado because of the law of energy conservation. Chaos theory only sets some limit to weather forecasting but did not reject any possibility of weather forecasting.

Empirical studies of economic chaos

A fierce debate began in economics is the existence of economic chaos and its meanings to economic theory, since the implications of economic chaos would challenge basic beliefs in neoclassical economics and econometrics.

In 1984, a numerical algorithm for estimating fractal dimension from empirical data was developed (Grassberger and Procaccia 1984), and the first empirical evidence of climate attractor was discovered (Nicolis and Nicolis 1984). The author began to search economic chaos from empirical data in 1984. Empirical and theoretical evidence of economic chaos was first discovered from monetary index in 1987, and wide evidence from macro and finance indexes in 1996 (Chen 1987, 1988).

There was a big controversy in empirical research of economic chaos. There are several issues that are unsolved in economics and physics.

High noise level from economic indexes and
noise-cycle separation in 2D time-frequency space

Most empirical evidence of deterministic chaos was discovered from lab experiments in fluid dynamics, chemistry, and physiology. Evidence from non-experimental data such as climate attractor and economic chaos was controversial since their results were hard to verify.

The first wave of empirical tests was based on numerical algorithms in physics, such as Lyapunov exponent and correlation dimension, which were not useful in economic research. The main difficulty is high noise level in economic data. Physics test of chaos require large number of data with very low noise, where high frequency economic data with low noise level were hardly exist.

Physicists also use frequency spectra to detect sub-harmonic frequency from continuous-time deterministic chaos. However, Fourier analysis in physics and engineering can only analyze stationary time series that can be obtained from lab experiment, but not non-stationary time series from non-controllable observations, such as radar signal from moving targets. We could separate noise with cycles from economic data by means of new algorithm of time-frequency analysis based on Wigner transform in Gabor two-dimensional time-frequency space because its base function is Gabor wavelet with minimum uncertainty in quantum mechanics (Qian and Chen 1996, Chen 1996a). Unfortunately, physics algorithm of time-frequency analysis is only available in Matlab under patent protection by National Instrument, but not available from econometric software packages. Few economists have the tools to verify our results. This is why obsolete math is still dominant in mainstream economics when economists lack new tools from physics and engineering.

White chaos in discrete time vs. color chaos in continuous time

The second wave of empirical tests of chaotic models was a big failure, since econometric tests based on regression analysis based on discrete time difference equation had no empirical evidence. Empirical tests of logistic map and Henon map made no success. The mainstream economics quickly accept the premature conclusion that economics had little evidence of economic chaos based on conflicting evidence from econometric tests and physics tests (Broke and Sayers 1988).

We found several sources that make economic chaos hard to observe by conventional methods.

Economists used to econometric models in discrete time, few economists had mathematical knowledge in solving nonlinear differential equations and spectral analysis of time series. Economists fail to know that there are two types of deterministic chaos in math models. “White chaos” from nonlinear difference equations, which has flat spectra that looks like white noise. White chaos could only observe from numerical solutions from simple theoretical models but no empirical evidence of white chaos, since we do not have real dynamics in fixed discrete time. All observed empirical chaos is “color chaos” from continuous-time differential equations, which has a fat peak plus noisy background in frequency spectra. The reason is simple since we do not have a theory of “quantum time” with fixed time unit.

We found low-dimensional color chaos from monetary and finance indexes that can be explained by delay-differential equations in continuous-time (Chen 1988, Chen 1996a) that was first discovered from biological chaos (Mackey and Glass 1977). It implies that economic dynamics is more complex than climate dynamics, since 1D delay-differential equation is a mixed difference-differential equation, its numerical solution needs to calculate infinite-dimensional of differential equations. And numerical solution of 1D differential equation needs to calculate infinite-dimensional difference equations. Mathematical physics knew delay-differential equation first from neuron dynamics, later from biological chaos such as cell vibrations. Economic mathematics is far behind chaos study since economic models are mainly confined by difference equations and regression analysis.

The Copernicus problem in macro and finance analysis

There is an unsolved Copernicus problem in macro-finance analysis that is caused by a growing trend in many economic time series. Three competing schools in business cycle theory used different types of filter to transform a macro time series with growth trend into stationary time series without trend. Keynesian economists follow Solow’s method of log-linear detrending that implies a constant growth rate in macro economy, which is different within different time windows. Econometricians follow the monetarist Friedman’s method of FD (first-differencing) of logarithmic time series, which implies no growth trend within a time unit. RBC school used the HP filter to separate a smooth trend and business cycles within a range of 2-10 years according to NBER business cycle chronology. We found wide evidence of color chaos mainly from HP filtered cycle series, but only white noise from FD series. The reason is very simple. HP cycles in average is about 4-5 years from US data that is the typical political cycle in U.S. Multiple frequencies were also observed that was consistent with Schumpeter theory of business cycles as biological clock.

The whitening filter in econometrics and white noise representation of efficient market

There is a philosophical bias that prevents economists to accept new evidence of economic chaos. Believers in efficient market assume white noise is the proper math representation for perfect competition (Friedman 1953b).

The FD filter is a whitening device, which amplifies high frequency noise and suppresses low frequency signals. Economists used to FD filter not only because of its mathematical simplicity, but also based on their belief in "invisible hand". Econometricians analyze economic data with a white looking glass. They fail to see a colorful world simply because they are color-blind.

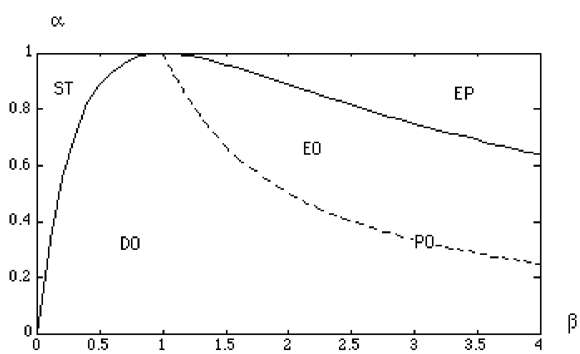
Computational economics with complex patterns

Advancement of computer technology paved the way for computer simulation in computational physics. There are three approaches in economic simulation with large systems. The first approach is system dynamics in management developed at Sloan School of MIT (Forrester 1961). The second is self-organization based on ecological dynamics developed by physicist in Brussels school (Allen and Sanglier 1981, Allen 1997). The third approach is called Complex Adaptive System (CAS) or agent-based model developed at Santa Fe Institute, which is a computer automata originated in artificial life (Arthur, Arthur, Durlauf, and Lane, 1997). Computer simulation could generating many interesting features, such as complex behaviour caused by simple interaction rules, emergence of communities and cities, diversifying patterns in geography, and erratic fluctuations in stock market, etc. (Arthur 2015, Wilson and Kirman 2016, Aruka and Kirman 2017). Their challenge is how to identify specific mechanism from empirical observation and experiments.

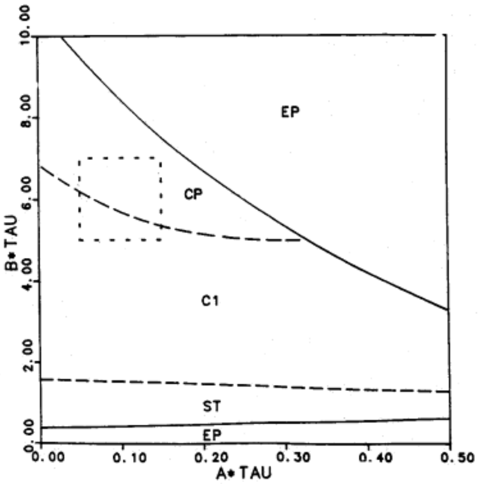
Persistence of biological clock and resilience in regime switch

One fear created by chaos and complexity is their image of disorder and destruction. We found out that new kind of order can be characterized by Schumpeter's idea of biological clock in business cycle theory and resilience in regime switch through crisis.

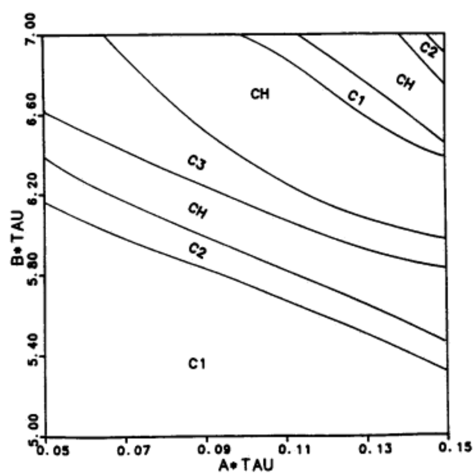
First, linear model of the periodic solution in Samuelson model and the unit-root in econometrics are fragile or marginally stable, since they are valid only on the boarder or edge between stable and unstable regime. Any disturbance in parameter space would drive the cycle or unit-root solution into damped or explosive regime. But chaos regime with multi-frequency could exist in a stable regime with finite area in parameter space (See Fig. 2).



(2a) Stability pattern of Samuelson model in parameter space (1939). Here, ST denotes the steady state; DO, damped oscillation; EO, explosive oscillation; EP, explosive solution; PO, linear periodic oscillation.



(2b) Parameter space for soft-bouncing oscillator (Chen 1988). ST denotes the steady state. CP is the complex regime including multi-periodic states C1, C2, C3, etc.



(2c) The expanded regime in (2b). C1, C2, C3 are limit cycles of period one, period two, and period three respectively; CH, the chaos mode in continuous time.

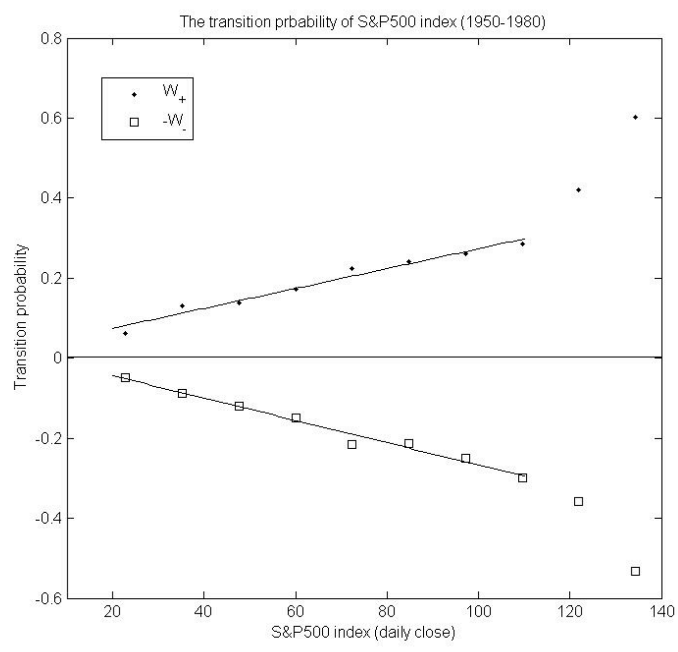
Fig. 2. Structural stability in parameter space. (2a) Periodic solution PO is only marginally stable at the borderline. (2b) Complex and chaotic regime is structurally stable within the area of CP. The complex regime CP in (2b) is enlarged in CH in (2c) that consists of alternative zones of limit cycles and chaos.

Clearly, PO (periodic oscillation) state in linear Samuelson model is fragile since PO regime located on the edge between BO and EO regime. In contrast, CP and CH (chaos) states are resilient within finite zones in parameter space. CP and CH modes are viable when parameter changes within their dynamical zones.

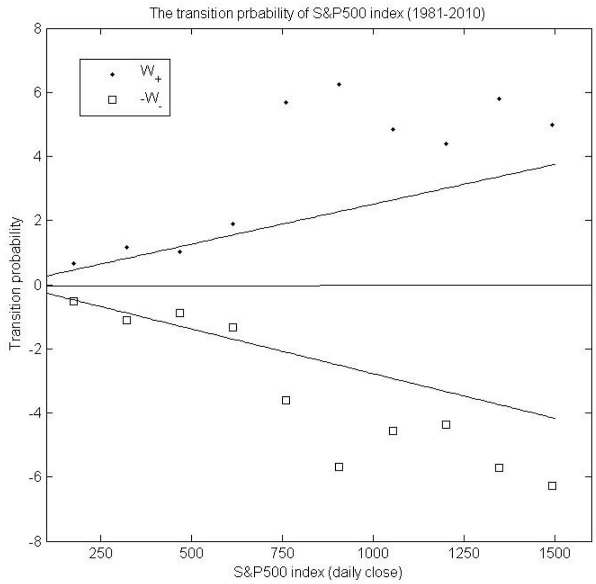
Multi-regimes of market and phase transition during crisis

How to understand the resilience of financial market enduring recurrent crisis? We found multi-regimes in financial market. The calm regime and turbulent regime can be identified from financial indexes where a phase transition occurred during the financial crisis (Tang and Chen 2015).

We find out the master equation in statistical mechanics is capable of understanding both calm and turbulent market in finance (Tang and Chen 2015). In nonlinear stochastic dynamics, we found out that the population model of the birth-death process is persistent in time, while the representative model of random walk and Brownian motion is either damping or explosive in time. The transition probability in different periods can be seen from Fig. 3.



(3a) Transition probability in (1950-1980).



(3b) Transition Probability in (1980-2010).

Fig. 3. Transition Probability for Calm (1950-1980) and Turbulent (1980-2010) Market Regimes.
The horizontal axis is the price level of the S&P 500 daily index. The vertical axis is the transition probability at varying price level. Data source is S&P 500 daily close prices.

From Fig.3, the upper curve can be explained by the "strength" with positive trading strategy, and the lower curve the strength with negative trading strategy. Intuitively, net price movements are resulted from the power balance between the "Bull camp" and the "Bear camp". There is remarkable difference between Period I (1950-1980) and Period II (1980-2010). Fig.3a is smoother than Fig.3b. The significant nonlinearity in Fig.3b is a visible sign of turbulent market that may produce financial crisis. Clearly, liberalization policy in Period II is closely related to the 2008 financial crisis in the sense that deregulation stimulated excess speculation in financial market.

We can solve the master equation of the birth-death process and find out the break point of the distribution probability. Our numerical solution indicates that the market breakdown occurs at the Sept. 25, 2008, when the Office of Thrift Supervision (OTS) seized Washington Mutual. This event was the peak from chain events preceding the 2008 financial crisis. The stock market went to panic since 26-Sep-2008. Our result is well compatible with historical timeline.

Empirical patterns and statistical mechanics in econophysics

A new wave of applied physics in economics created a new field of econophysics (Mantegna and Stanley 2000). The early case of economics studied by physicists was the St. Petersburg paradox in decision theory in economics (Bernoulli 1738, 1954). Another example is the game theory (Morgenstern and Von Neumann 1948). The main discovery in econophysics was the empirical evidence of power law in a wide range of economic data (West 2017). New techniques in studying economics and finance are introduced, such as random matrix (Plerou et al 2002), log-periodic power law singularity (Sornette 2003), and economic complexity index (Hausmann and Hidalgo 2009).

Unsolved issues in statistical mechanics: social temperature vs. social interactions

It is too early now to evaluate numerous findings from econophysics, since the fundamental differences between economics and physics have yet to determined. For example, the Ising model of ferromagnetism was applied in social psychology and social dynamics (Weidlich 1972, 2006). The problem is that the social temperature was a concept for equilibrium system with conservation of energy. Social system is non-equilibrium open system without conservation of energy.

There is an interesting case that difference in "income temperature" can be defined by exponential distribution from US and UK income distribution (Yakovenko 2009). The author suggested that a thermal machine could operate between a high income-temperature country like the US and a low income-temperature country such as China. The perpetual trade deficit of the US could be generated by thermodynamic machine in non-equilibrium economies. The problem is that international trade is more complex than physics. China had persistent trade deficit with Japan but big surplus with the U.S., while both US and Japan are developed countries. Income temperature alone may not explain opposite patterns in trade imbalance between high and low income countries. Technology gap, product chain, and other factors may also play roles in trade imbalance. Perhaps physicists could define a vector temperature with several components to characterize disequilibrium not just in income, but also in resource, technology, finance, and military power in global competition.

We did try an alternative approach in study non-equilibrium statistical mechanics. To apply master equation approach in statistical mechanics in social systems, we adopt an alternative measure of temperature by intensity of social interaction. We found U-shaped distribution that is similar to the polar distribution in Ising model of social psychology (Chen 1991). See Fig. 4 and Fig. 5.

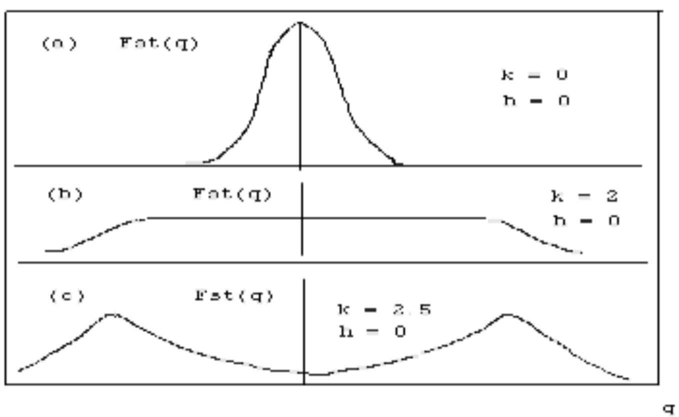


Fig.4. The steady state of probability distribution function in the Ising Model of Collective Behavior with h=0 (without central propaganda field).

(a) Uni-modular distribution with low social stress (k=0). Moderate stable behavior with weak interaction and high social temperature.

(b) Marginal distribution at the phase transition with medium social stress (k=2). Behavioral phase transition occurs between stable and unstable society induced by collective behavior.

(c) Bi-modular distribution with high social stress (k=2.5). The society splits into two opposing groups under low social temperature and strong social interactions in unstable society.

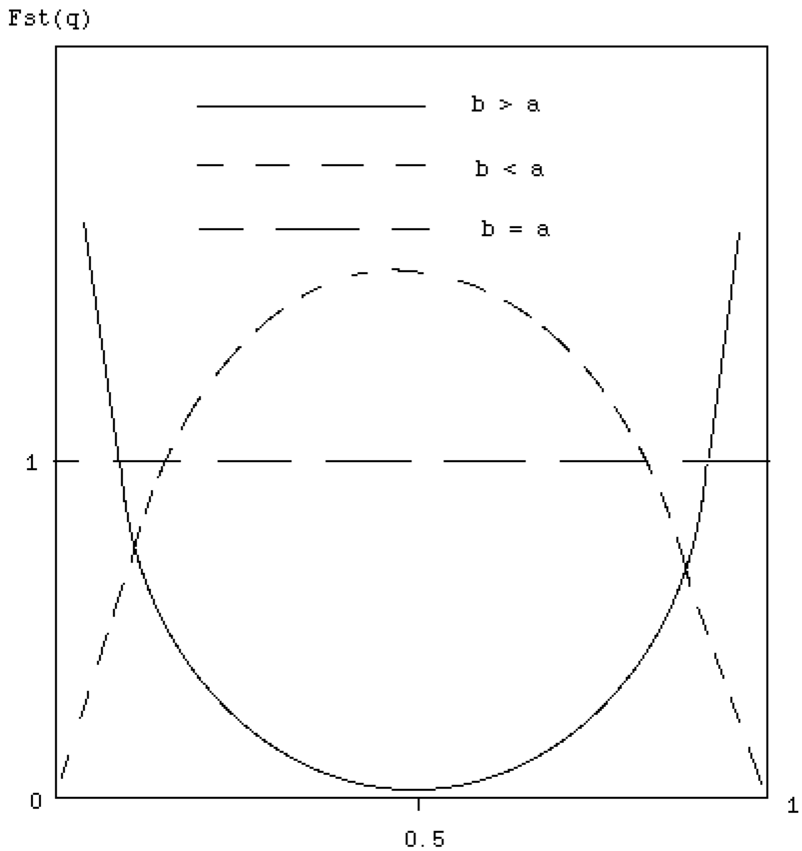


Fig.5.The steady state of probability distribution function in socio-psychological model of collective choice. Here, “a” is the independent parameter; “b” is the interaction parameter.
(a) Centered distribution with b < a (denoted by short dashed curve). It happens when independent decision rooted in individualistic orientation overcomes social pressure through mutual communication.
(b) Horizontal flat distribution with b = a (denoted by long dashed line.) Marginal case when individualistic orientation balances the social pressure.
(c) Polarized distribution with b > a (denoted by solid line). It occurs when social pressure through mutual communication is stronger than independent judgment.

Power law, fat-tail, black swan, and edge of chaos?

Another problem is the implication of fat-tail distribution and power law in finance, since it implies huge instability and uncertainty.

In history of science, quantum biology made tremendous success by discovery of generic code from molecule biology. We need similar theory to explain why power law observed in fluid dynamics can be allied to biology and economics. The universe seems to have a multi-level structure. Physicists should be careful, since economic complexity could be more complex than existing physics models.

The principle of large numbers and
meso foundation of macro fluctuations

Structure analysis plays an important role in physics and biology. However, structure is missing in macroeconomics. The so-called microfoundations theory simply asserts that macro dynamics should follow the same behavior in microeconomics without intermediate structure. We found three-level structure of micro-meso-macro in business cycle theory that is revealed by Schrödinger's Principle of Large Numbers (Schrödinger 1948, Chen 2002)

One fundamental issue in macro and finance theory is the origin of business cycles and the cause of the Great Depression. Lucas claimed that business cycles or even the Great Depression could be explained by workers' choices between work and leisure, which is called the micro-foundations theory of (macro) business cycles. Schrödinger proposed a simple math that reveals the relation between the number of microelements and the degree of aggregate fluctuations. We define the relative deviation (RD) as the ratio of the standard deviation to its mean when the underlying variable has only positive value, such as price and volume.

$$RD = \frac{STD(S_N)}{\sqrt{N}} \qquad \text{Eq. (3.1)}$$

Here, RD stands for relative deviation for positive variable, STD is standard deviation, which is the square root of the variance of a variable S with N elements: $S_N=X_1+X_2+\dots +X_N$.

The idea is quite simple. The more element number N at the micro level, the less will be the aggregate fluctuation at the macro level, since independent fluctuations at the micro level would largely cancel out each other. We call this relation as the principle of large numbers. We extend this relation from static system to the population dynamics of the birth–death process. We first calculate RD from an economic index through the HP filter. Then, we estimate the effective micro number N. The result is given in Table 3.1, which can be used for diagnosing financial crisis.

Table 3.1 Relative Deviation (RD) and
Effective Number (N) for Macro and Finance Indexes

Item	RD (%)	N
Real personal consumption	0.15	800,000
Real GDP	0.2	500,000
Real private investment	1.2	10,000
Dow Jones Industrial (1928–2009)	1.4	9,000
S&P 500 Index (1947–2009)	1.6	5,000
NASDAQ (1971–2009)	2.0	3,000
Japan–US exchange rate (1971–2009)	6.1	300
US–Euro exchange rate (1999–2009)	4.9	400
Texas crude oil price (1978–2008)	5.3	400

In comparison, the number of households, corporations and public companies and the potential RD generated by them are given in Table 3.2.

Table 3.2 Numbers of Households and Firms in US (1980)

Micro-agents	Households	Corporations*	Public companies
N	80,700,000	2,900,000	20,000
RD (%)	0.01	0.1	0.7

* Here, we count only those corporations with more than $100 000 in assets.

From Tables 3.1 and 3.2, household fluctuations may contribute only about 5 percent of fluctuations in real gross domestic product (GDP) and less than 1 percent in real investment; and small firms can contribute 50 percent of fluctuations in real GDP or 8 percent in real investment. In contrast, public companies can generate about 60 percent of aggregate fluctuations in real investment. Clearly, there are very weak 'micro-foundations' but strong evidence of a 'meso-foundation' in macroeconomic fluctuations.

In another words, large macro fluctuations in macro and finance can only generated by fluctuations at the meso (finance) level, not the micro level from households or small firms. Extremely large fluctuations in commodity and currency market can only be caused by financial oligarchs. This is the root of 2008 financial crisis.

Our approach finds strong evidence of meso (finance and industrial organization) structure from macro and finance indexes. Our three-level system of micro-meso-macro is better than the two-level system of micro and macro in Keynesian economics in studies of structural foundation of business cycles and crisis.

Conflicting perceptions of economic information

Economists and physicists have different understanding about the nature and sources of information.

For physicists, any meaningful information is associated with deterministic signals such as waves and codes with clear pattern. Shannon's information entropy based on probability theory is a measure of ignorance rather than knowledge (Shannon 1948). That is why Schrödinger used the term of "negative entropy" to characterize information as decreasing ignorance (Schrödinger 1948).

In contrast, economists used the term of information in four different ways.

In microeconomics, the concept of "complete information" in "perfect market" implies a Laplace world of Newtonian determinism. It is only possible in a closed system like chess game, where any innovation and uncertainty was ruled out. No entry or exit of new product, new technologies, new players, plus no rule of changes could occur in the idealized market.

In growth theory and macroeconomics, random variables are treated as driven force of business cycles in the form of "innovation" in real business cycle or monetary shocks in monetary theory. More strangely, the Solow residual in growth accounting is simply a black box with a nice name of "the total factor productivity." No any model in physics and biology would consider random noise as the driving force of growth and development. Since random movement is the feature of heat, a form of disorganized energy.

Brownian motion also plays a central role in finance theory. There is no logical link between basic variables in financial market and erratic movements of stock price. Financial market used to treat random shock as rumors rather than information behind price fluctuations.

Only RBC economists tried to separate noise and cycles along a nonlinear trend (Hodrick and Prescott 1997). Their approach reveals the Copernicus problem in selecting observation reference system in macro and finance.

If economists and econometricians have basic knowledge in information theory and signal processing technology, economic analysis and theory would be more pragmatic to real world.

We need further discuss the philosophical background of conflicting information theories in economics.

Information costs and bounded rationality

It is known in quantum mechanics that any information collection and transmission is associated with finite energy. There is no chance in physics world that complete information can be obtained without energy costs. The idealized world of perfect market with complete information and rational expectation in economics is impossible in physics world, since dealing with complete information in a global market needs a super computer with infinite speed plus infinite memory, and consuming infinite energy. Any realistic human being or artificial intelligence could only have bounded rationality (Simon 1984). This is a common sense among computer scientists and electrical engineers. Unfortunately, economic thought experiments like rational expectations and Friedman spirits simply assumed perfect rationality could operate without energy dissipation in communication.

The Friedman spirits in market arbitrage and
the Maxwell demon fighting market uncertainty

A thought experiment for basic belief in a stable and efficient market was created by Friedman in discussing the self-stability of a flexible exchange rate regime. The central idea could be characterized by Friedman spirits, which were rational arbitrageurs capable of driving out irrational (destabilizing) speculators (Friedman 1953). This is the main argument for the efficient market hypothesis in macro and finance dynamical theory.

Friedman spirits behave much like the Maxwell demon in equilibrium thermodynamics (Chen 2008). The Maxwell demon is an imaginary gatekeeper trying to create a non-equilibrium order from an equilibrium state by operating a frictionless sliding door between two chambers that are filled with moving molecules (Maxwell 1971). Maxwell assumed that his demon had perfect information about the speed and position of all molecules such that he could allow only a fast molecule into a designated chamber by opening or closing the mass-less valve in perfect timing. In economic language, under the condition of perfect dynamic information, the Maxwell demon could create a temperature difference without doing work, though that outcome is contrary to the second law of thermodynamics. The meaning of perfect information is also essential for a Coasian world with zero information costs (we will return to this issue in next section).

Friedman spirits face a similar problem to that of the Maxwell demon but with an opposite task. To eliminate any market instability, Friedman spirits had two problems in achieving their goal.

First, resource limitation is a severe barrier in defending speculative winds with positive feedback strategy, i.e., the recurrent market fads by following the crowd (Shleifer and Summers 1990). For example, foreign reserves in any central bank are limited compared to speculative capital in the global financial market.

Second, the uncertainty principle and dynamic complexity set fundamental limits in duplicating disequilibrium portfolio in a competitive market. Friedman implicitly assumed that a winner's imitator could quickly drive down profit margins to zero. This strategy could work only if the winning pattern was replicable.

There are two fundamental difficulties in doing so. One problem is timing uncertainty in the frequency domain. The strategy of buying low and selling high works if the turning points of a speculative wave are predictable with small error. This possibility is limited by the uncertainty principle in terms of the trade-off between time resolution and frequency resolution (Qian and Chen 1996). Another barrier is complexity in the time domain. The sources of complexity in time series analysis include imperfect information (finite data with noise and time delays), information ambivalence (conflicting news and distorted information), unpredictable events (financial crisis and changing structure), and limited predictability (caused by deterministic chaos or wavelets). Information ambiguity is not only associated with bounded rationality but also rooted in dynamic complexity (Simon 1957, Chen 2005).

In short, the Friedman Spirit cannot ensure an efficient market. Unpredictability and ignorance do not lead to market efficiency.

Mixed economies and cooperative partnership in facing information uncertainty and changing society

In this perspective of bounded rationality, any market decision is a learning process with trial and error. Neither entrepreneurs nor government officials could make optimal solution in resource allocation. Therefore, market failures with invisible hand and government failures with visible hand are inevitable in adapting to changing technology and environment. Private ownership and incentive mechanism alone is not sufficient to deal with natural disaster, environmental crisis, and social instability when market uncertainty and coordination costs are too large to be bear by individuals, firms, and small communities. Institutional economics lacks theory in dealing with mixed economies including public, private, non-profit organizations, and international cooperation. Clearly, market forces alone are not capable in solving long-term problems, such as infrastructure investment, economic development, and poverty. Economics should be more inclusive in addressing contemporary issues in developing and developed world. Equilibrium approaches cannot understood the failure of Washington consensus in Latin America and the transition depression caused by the Shock Therapy in East Europe and Soviet Union (Williamson 1990) Mainstream economists behave like a witch doctor who treats different diseases with a standard medicine called equilibrium policies, such as privatization, liberalization, and macro stabilization, regardless of economic complexity and political risk in far from equilibrium conditions (Stiglitz 2010). In contrast, developed countries never apply the similar equilibrium policies in dealing with the 2008 Great Recession in their own countries.

Perpetual motion machines in equilibrium economics

There are three types of Perpetual Motion Machine widely used in mainstream economics that violate basic laws in thermodynamics.

General equilibrium mechanism without energy costs

Both Walras model and Arrow-Debreu model of general equilibrium is a static model with many variables without time trajectory and interaction speed in economic dynamics. It implies an infinite speed in price adjustment. If the general equilibrium model works in real economies, this would be the perpetual motion machine of the first type, since instantaneous interaction means infinite speed of communication without dissipation of energy.

In real experiment, the shock therapy applied in transition economies in East Europe, the stabilization period varied from seven years in Poland to more than twenty years in Ukraine depending political and historical conditions (Chen 2006).

Frisch model and perpetual motion machine in econometrics

The Frisch model of noise-driven cycles is a perpetual motion machine of the second type, which is a thermal machine with only one heat source. We knew from second law of thermodynamics that Carnot heat engine can transfer heat from high temperature into work at the cost of waste heat released at low temperature. But Frisch imagine a heat engine could do work (keeping pendulum oscillating) by only one heat source (Frisch 1933). Noise or external shocks became the very foundation of econometrics, finance, and DSGE model in macro dynamics. Even macro growth is driven by noise with a magic name of innovations.

We found that the Frisch model was a fake model discredited by physicists before and after him (Uhlenbeck and Ornstein 1930, Wang and Uhlenbeck 1945). In fact, Frisch never formerly published his promised paper in Econometrica and did not even mention his prize-winning model in his Nobel Lecture. The strange success of the Frisch model in economics is a historical puzzle in the history of Nobel economics when an alchemy model was treated as a science (Chen 1998, 2010, 2016).

The Coasian world with zero transaction costs,
an equilibrium utopian with one-way evolution

The Coase theory of transaction costs had an implicit assumption that market competition would drive down transaction costs to zero, a utopian market without conflicts and government regulations (Coase 1988). Coase assumed that bargaining mechanism could solve all conflicting issues in social exchange without the need of government regulation or violence. It sounds like a perpetual motion machine of the third kind. Darwin would surprise to see a strange world where wolf and lamb could peacefully coexist and social animals all disappear. Existence space in living world could be divided and maintained without conflicts under free exchange without energy costs.

The Coase world of zero-transaction cost is a utopian world without friction. The concept of transaction costs is equivalent to physics concept of heat or entropy in thermodynamics, when organized energy is transferred into disorganized heat by overcoming friction. There is a visible trend of increasing energy dissipation in industrialization that is the root cause of global warming. If Coase were right, then market forces alone would solve the problem of global warming. So far, we did not have any convincing evidence.

First, the Coasian world of zero-transaction costs cannot exist in the real world since it violates several basic laws in physics. The frictionless world is realistic for planet motion in space but not possible in living world, since living organization is maintained by dissipative structure with constant matter flow, energy flow and information flow (Prigogine 1980, Chen 2007). The analogy between a frictionless world in physics and the Coasian world with zero transaction costs is wrong, since zero information cost is impossible for information collection in a living world according to the uncertainty principle in quantum mechanics (Brillouin 1962). Any information collection or transmission requires some form of energy. Coase believed that a frictionless world could constantly move without energy input. He did not even understand the Newton's law: both acceleration and deceleration are driven by forces that consume energy. How could a train keeps running without stop and restart? The Coasian world is another example of a perpetual motion machine in equilibrium economics (Chen 2007).

Second, economists observed a trend of increasing transaction costs in modern society. For example, transaction costs in the US GDP increased from about 25% in 1870 to more than 50% in 1970 [Wallis and North 1986]. The core of transaction costs is marketing costs and information costs in division of labor. Coase made a hidden assumption that market competition would drive down transaction costs. He seems to ignore counter business strategies, such as marketing strategy for creating value and expanding market share, at the cost of increasing transaction costs. Technological progress may reduce the unit transportation cost and communication cost; but aggregate transaction costs as a whole may increase when network complexity and innovation uncertainty growing with technology progress.

Third, the most controversial assertion in the Coase Theorem is that any social conflicts could be resolved by bilateral bargaining without the third party (law, government, or civic society) intermediation (Coase 1960, 1988). His argument was based on the symmetry between polluter and victim, and more generally, the symmetry between consumption and investment (Coase 1960, 1988, Cheung 1998). If the Coase Theorem were valid, there would be no power, no conflicts, no war, no government, and no regulations. This may be true for primitive society without private property and wealth accumulation, but is not true for a competitive but unequal market economy. Coase made the claim of observing the real world. After careful examination, we found out that no single case studied by Coase could support his claim. Bilateral bargaining under a specific context could not converge to an (universal) optimal state when asymmetry exists in the form of non-convexity, such as scale economy in a cattle ranch, upward-demand for pollution compensation, and social dissent for commercial bribery. Coase argued that price theory could be applied to the externality problem if the demand curve is always negatively sloped (Coase 1988). Coase did not understand why market breaks down. The history told a much simpler story. If people fight for existence, no room left for Pareto optimum.

Complexity Study and New Economic Thinking

Until now, studies on economic complexity only made limited impact to mainstream economic thinking, but a paradigm change is forthcoming.

Increasing returns and path dependence in economy

The most visible impact was the existence of path dependence and increasing returns to scale in economy such as the notable example of Silicon Valley (David 1985, Arthur 1994). The question is whether rigid increasing returns in AK model can be integrated into optimization approach in neoclassical economics (Krugman 1980, Romer 1986), or we need an alternative framework to address the larger picture of technology evolution. This issue can be solved with dynamic model with varying returns to scale in next section.

Dynamic returns to scale and metabolic growth theory

Conflicting predictions from neoclassical growth theories were resulted from static returns to scale. The Solow model of exogenous growth predicted a convergence trend in economic growth based on the assumption of constant returns to scale (1957), while the Romer model of endogenous growth claimed a divergence trend based on increasing returns to scale in knowledge accumulation (Arrow 1962, Romer 1986). In history, observed patterns of rise and fall of great nations in history are more complex than the predictions of neoclassical growth models. However, learning by doing and knowledge accumulation ignores the interruptive nature of technology advancement. We developed a theory of metabolic growth (Chen 2014).

We introduce dynamic returns to scale based on the logistic model in ecology. An emerging technology can be described by a S-shaped logistic curve with resource limit in ecology. A new technology competition with higher resource limit would drive old wavelet into decline or die out. The rise and fall of technologies and industries can be seen from Fig. 6.

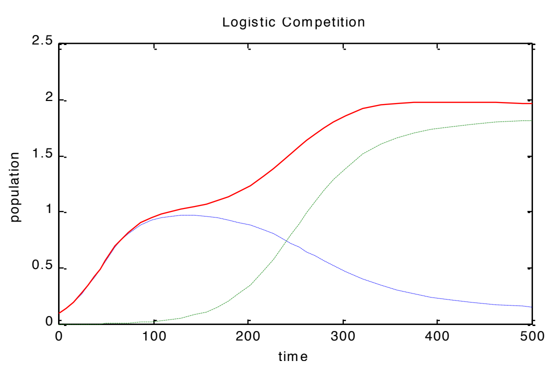


Fig.6. Metabolic growth characterized by technology competition with logistic resource constrain. The old technology (blue dashed line) declines when new technology (green dot and dash line) emerges. The output envelope (red solid line) is the sum of their output of all technologies. Here, the units here are arbitrary in

computational simulation.

Creative destruction of new technology and life cycle of logistic wavelets

Creative destruction can be understood by knowledge metabolism (Schumpeter 1950). The wavelet representation can be applied in analyzing the lifecycle of products, firms, technologies, and nations. The time scale of the logistic wavelet varies between product life cycles from several months to Kondratieff long waves over several decades. The wavelet is a better model than noise and cycles in economic dynamics, since it provides a unified theory in micro, meso, macro, and clio economics.

We may divide the logistic wavelet into four stages: infant, young, adult, and old stage. Government policy has to adapt to changing market in these stages, just like the relation between parents and growing kids. Similarly, institutional arrangements must adapt to different stages of technology life cycles. Both market and governments have to learn through trial and error in order to adapt to changing technology. The co-evolution of technology, environment, and regulation in complex economic system is more realistic than the utopian picture of Pareto efficiency, since we should consider the balance among long-term ecological sustainability, medium-term social stability, and short-term economic efficiency.

Rethinking Adam Smith and Return to Political Economy

The contemporary issues of global warming and persistent poverty revived the original thoughts of classical economists from Smith, Malthus, to Darwin and Marx (Pikkety 2014). People realized that important issues in political economy could not be marginalized by neoclassical economics. We find fundamental contradiction existed in Adam Smith theory of Wealth of Nations (Smith 1776).

Bifurcation between classical and neoclassical economics

We realized that classical economics and neoclassical economics are conflicting in economic perspectives.

First, classical economics is nonlinear in nature, since economics was constrained by resource limit. Smith theorem clearly stated, “the division of labor is limited by the extent of market” (Smith 1776, Stigler 1951). Malthus further emphasized the resource constrain to population growth (Malthus 1798) that inspired the evolution theory in biology (Darwin 1859). In this regard, economic dynamics should build on theoretical ecology with resource limit that is the very foundation of ecological economics. However, linear models in neoclassical economics assume unlimited resource so that “economic man” could be “selfish” and “greed” with unlimited want in material consumption. The basic assumptions on human nature are simply against basic knowledge in evolutionary biology and evolutionary psychology. That is why economic chaos could not exist in neoclassical economics, but compatible with classical economics with nonlinear constrains in market extent and natural resource.

Second, political economy is the essence of classical economics when Smith quoted Hobbs that “wealth is power” (Smith 1776), since resource competition can be won by economic, political, and military powers. In contrast, neoclassical economics abstracts away of political, cultural, and social background of economic decision and institution by value-neutral assumptions in economic behavior. A notable example is the trade war and colonial war that are inherited in market share competition with increasing returns to scale, while the general equilibrium framework in microeconomics (Arrow and Debreu 1954) and transaction cost theory (Coase 1988) simply rule out multi-equilibrium and conflicts in economic theory. Now we knew the existence of increasing returns to scale would not have a unique stable equilibrium.

Clearly, the problem with neoclassical economics is not using “too much math” but using “improper math, since the linear and optimization approach in neoclassical economics is not capable in dealing with economic evolution with resource constrains. We apply basic tools in complex systems and non-equilibrium physics to analyze basic theories in neoclassical economics. We made fundamental progress in developing a new paradigm for economic theory. We could reformulate economic theory based on more general math framework in nonlinear dynamics and non-equilibrium physics (Chen 2010, 2016).

Complexity in Division of Labor and Perplexity in Trade Imbalance

Economic complexity sheds new light to understand fundamental issues in Adam Smith theory of "Wealth of Nations" (Smith 1776) that was born with complexity and fantasy. There were thee perplexities caused by economic complexity.

First, the market-share competition in division of labor is the destabilizing cause of market stability, since increasing efficiency in production implies increasing risk in product marketing when production capacity could not fully utilized by export market. This is the root of trade war and government subsidy for stabilizing commodity price. For example, the U.S. had persistent trade deficit since 1970s. Flexible exchange rate and interest rate could not balance the international trade. The structural dis-equilibrium in international economies could not explained by equilibrium theory.

Second, Smith' theory of "invisible hand" was based on the symmetry assumption in international trade. Smith naively believed that the return ship would bring commodities back to export country to balance the trade, but he had no reason to believe the two-way trade would have equal value. In history, Britain had persistent trade deficit to China for 170 years. Britain used visible hand to balance the tea-trade with China by launching Opium War, tea plantation in India, plus Indian railway subsidized by British colonial government (Pomeranz and Topik 2006). Current trade war under President Trump is a good lesson to the limit of invisible hand in international trade. We need study the real cause of market instability in complex economic systems.

There are numerous asymmetries exist in economic complexity that breaks down general equilibrium in market economy. For example, income and wealth disparity between import and export countries play important role in trade imbalance. The U.S. could maintain persistent trade deficit because the dollar has a monetary power as reserve currency. Supply and demand forces are not symmetric because life cycle asymmetry is significant in business cycle since production cycles are much longer than consumption cycles. Uneven technology creates more disparity in economic development. The general equilibrium theory is an economic utopian with symmetric demand and supply within an equal society. It could not address contemporary issues of global warming, ecological crisis, and financial crisis.

Smith theorem and Smith dilemma in division of labor

In this sense, the Smith theorem is compatible with Malthus and Darwin with resource limitation of the market, while the Smith doctrine of self-stabilized market by invisible hand is incompatible with scale economy that is nonlinear in nature with complexity and diversity. The nonlinear model of ecological system provides a better alternative than the AK model with unlimited growth.

We found out that the rigid AK model with fixed returns to scale could not explain historical pattern of economic growth. The Solow model of exogenous growth predicted a convergent trend under constant returns to scale (1956), while the Romer model of endogenous growth implies a divergent trend under increasing returns of scale (1986). In order to explain observed patterns of rise and fall in technologies, a better model is dynamic returns of scale in metabolic growth with ecological constraints (Chen 1987, 2014).

We proposed the generalized Smith theorem in complex economic systems. The division of labor is limited by three factors, including market extent (or resource limit), resource diversity (number of resources), and environmental fluctuations. There is a trade-off between complexity and stability. There may be a two-way evolution (or co-evolution) process towards complexity or simplicity in division of labor under nonlinear evolutionary dynamics. When social stability is high and new resources keep coming, the system may develop into a complex system, like the Industrial Revolution in the past. However, when social turmoil is high or resources are used up due to over population, a complex system may break down into a simple system, such as the collapse of the Roman Empire in the Middle Ages. This is the theoretical foundation for understanding diversity of civilizations and cultures in history. In this perspective, metabolic growth theory is more close to evolutionary economics, institutional economics, and anthropology, than the equilibrium perspective in neoclassical economics.

Return to political economy: from Smith question to Hobbs answer

We realized that Smith raised the question on "wealth of nations", but failed to provide an answer. Instead, Smith quoted Hobbs that "wealth is power." This answer fall into the tradition of political economy that divides classical economics and neoclassical economics. The later tries to define economics as a value-free science without background in history, culture, and politics.

The generalized Smith theorem and
trade-off between stability and diversity

For complex ecological systems with many species and technologies, increasing the number of technologies will reduce system stability (May 1974). There is a trade-off between diversity and stability. We propose a generalized Smith Theorem (Chen 2010, 2014). The division of labor is limited by three factors, including the market extent (resource limit), bio-diversity (number of resources), and environmental fluctuations (social stability).

Neoclassical growth models have an one-way evolution to convergence or divergence under linear stochastic dynamics. In complex ecological systems, there may be a two-way evolution (or co-evolution) process towards complexity or simplicity in division of labor under nonlinear evolutionary dynamics. When social stability is high and new resources keep coming, the system may develop into a complex system, like the Industrial Revolution in the past. However, when social turmoil is high or resources are used up due to over population, a complex system may break down into a simple system, such as the collapse of the Roman Empire in the Middle Ages. Even in the modern era, industrial society coexists with traditional society and even primitive tribes. The interactions among population, environment, and technology lead to diversified patterns in civilization evolution.

Concluding remarks

The 2008 financial crisis had a wake-up call to economists that mainstream economics failed to understand the cause of business cycles and remedy of economic crisis. The World Economics Association was born to advance a more pluralistic and inclusive economics (WEA 2011).

There are several issues in economic methodology and future direction that are related to complexity economics.

The role of math in economic thinking

There is a strong critic that mainstream economics used too much math that was far from reality.

There are three lines of thinking about the role of math in economics. The first is the degree of math indicates its maturity in science. Therefore, using more math means more like a science in judging research papers in economics. This line of thinking is prevalent in the U.S. The second group took the opposition position. They argue that human behavior is too complex and math models are too simple. Therefore, economic ideas could not described by math language.

Our position belongs the third line of reasoning. Math is necessary to analyze increasing amount of data collected by business, governments, and researchers in the information era with big data. A useful graph or table with relevant economic data could tell a much clear picture than thousand words. The real issue is how to find a proper math tool to address meaningful economic questions. If your question is based on short-term price movements, then simple model of demand and supply may provide some clue. However, if your question is about medium-term investment and long-term development, or persistent problem of poverty and war, the linear model of general equilibrium has little answer except to avoid the political substance. In addressing fundamental issues in economics, nonlinear and non-equilibrium models are more powerful in diagnosing causes of instability and comparing different solutions.

However, economists should be aware the implications or limitations embedded in math assumptions. For example, the Brownian motion and the power law is stochastic model in nature. There difference lies in the probability of large deviations in real economy. However, they have a common implication that governments could to nothing to stabilize the market. That is why liberalization policy could be justified by math models like Levy distribution or power law, but rejected by historical experiments like the Great Depression and the transition depression in Eastern Europe. In this regard, history is a better judge than math to test competing economic schools.

Physics and biology foundation of economic theory

There is another critic of mainstream economics that neoclassical economics looks more like physics rather than humanity or social science. They argue that history, psychology, and anthropology are more relevant to economic studies.

Their critic has some merits since we do acknowledge that history, psychology, and anthropology reveals important factors in economic behavior and social changes. Future economic theory should integrate with other fields from history and social sciences. However, many scholars did not realize there are two kinds of physics: equilibrium physics in closed system and non-equilibrium physics in open system. Their behavior is fundamentally different.

The optimization approach in neoclassical economics did imitate Hamiltonian mechanics in closed system, which requires conservation of energy without friction. Its scope is smaller than Newtonian mechanics that permits nonlinear forces and friction. Therefore, deterministic chaos can be studied in classical mechanics, but not in equilibrium economics that excludes nonlinear mechanism and friction. In this regard, classical mechanics is a true science for real world but equilibrium economics is only alchemy or a religion with math cloth.

Marshall realized that economy is more close to biology rather than mechanics (Marshall 1920). However, linear model of demand and supply is only a static metaphor rather than dynamic model in biology or ecology. Nonlinear dynamics offers better model of nonlinear oscillator and wavelets to characterize biological clock and life cycle observed by economic historians like Schumpeter and NBER business cycle chronology. Hayek's idea of spontaneous order can be better described by self-organization, emergence, and phase transition in nonlinear and non-equilibrium model in nonlinear physics and theoretical ecology. In this regard, mainstream economics needs more proper and advanced math tools. Econometrics is far behind in math development, since it is confined by difference equation in discrete time, which fell behind Newton by using differential equations in continuous-time!

We should set a new standard to judge competing economic theories. Any realistic theory in economics should be compatible with physics laws and biology evolution. Neoclassical models are mainly utopian models of real economies when they assume unlimited resource, costless information, and infinite speed in equilibrium mechanism. Economists should abandon some misleading concepts, such as complete information, rational expectation, zero transaction costs, unlimited resource, and general equilibrium without diversity and changes, since these concepts violet basic laws in physics and biology.

Certainly, neoclassical models are useful in teaching methodology, since a nonlinear curve can be approximated by a broken line with many segment of straight lines, and a non-equilibrium situation can be approximated by an uneven picture with local equilibrium state changing in time and space. In this perspective, current models in mainstream economics could serve as special cases for a general economics with nonlinear mechanism and non-equilibrium framework.

Dialogue and complementation between complexity science and history

The real difficulty in complexity science is finding simple patterns from complex reality. This is the challenge to system theory and computer simulation, since more complex the model system, the less prediction based on complexity models. If anything were possible in computer simulation, practitioners would also feel helpless.

There are several directions for future complexity studies.

First, construct some simple indicator for characterizing complex phenomena. Notable examples are correlation dimension in chaos dynamics and information complexity with vector components. We need better economic indicators than current measure of per capita GDP that distort real picture of income inequality.

Second, we need identify major mechanism behind economic nonlinearity and nonequilibrium. Resource constrain is essential not only in growth theory, but also in utility function and behavioral preference. Human nature is a social animal because infant could not survive without assistance from parents and community. The rational man with unlimited greed could not survive in human evolution. Both competition and cooperation play critical role in human behavior. How to understand cooperation mechanism is an unsolved issue in economics. We already know that invisible hand of price system is not capable of coordinating in division of labor and international trade.

Third, economists and complexity scientists should pay more attention to political scientists and historian since they are more realistic in dealing with contemporary issues. They have no rare pleasure by playing math games without caring urgent issues in modern society. The contemporary issue is coordination of nations rather than wealth of nations, since wealth of powers created numerous conflicts and wars that threaten the existence of earth ecology and human society. Both nuclear weapons and financial derivatives are dangerous swords with double edges. They could open new resource or stabilize market, but they may also destroy the whole earth or create financial crisis. The blind faith in free market among mainstream economists had to face contemporary issues, like global warming, ecological crisis, poverty, and mass-destruction in recurrent wars.

In this aspect, I had tremendous admiration to my mentor Ilya Prigogine, who was a genius physicist with a shape sense in history. He was born in Russian evolution and witnessed the disaster of the WORLD WAR II in Europe. He told me that the equilibrium paradigm in physics could not square with history of war and revolution, which was non-equilibrium in nature. I was astonished by the general equilibrium economics in the U.S. when I moved from China to the States after experiencing a series of war and revolution. I found out that mainstream economists care little problems in the real world and better alternative was found from history and complexity science.

Emerging paradigm of a unifying theory in physics, biology, and economics

Einstein's special relativity and general relativity sets a role model for Keynes. If physicist could develop a general theory that included previous theory like Newtonian mechanics as the special cases of Einstein's general theory of relativity; Why could economists develop a general framework of dis-equilibrium economics that treats classical economics as a special case? This was the original dream of Keynes in his general theory (Keynes 1942).

Unfortunately, neoclassical synthesis and post-Keynesian economics went an opposite direction. They treat classical equilibrium economics as the general framework and Keynesian disequilibrium as special case such as liquidity trap and wage rigidity. They failed to develop a unified theory including normal business cycle as well as crisis and war. Keynes economics was born in wartime economics, but neoclassical economics refuses to face the reality from the Cold War to persistent arm race in the world. The basic demand-supply choice in Samuelson's textbook was between butter and cannon in 1950s (Samuelson 1955); and now became work and leisure in microeconomics and growth and debt in Reagan economics.

We are developing a GENERAL theory, which is compatible with fundamental laws in physics, ecology, biology, psychology, anthropology, and applicable in economics and management science (Chen 2010). Its main building block is logistic wavelet that is widely observed from life cycle in biology, ecology, and economy (Chen 2014). Evolutionary perspective developed by evolutionary economics, economic historian, and political economy can be integrated into complexity economics (Dopfer 2005). Studies in behavior economics and psychology are useful guide in modeling economic complexity (Arthur 2015). New tools in nonlinear dynamics, time-frequency spectra, and collective model of the birth-death process can be applied in diagnosis of financial crisis and advance warning in market regulation (Tang and Chen 2014).

History would tell whether complexity economics could go further than equilibrium economics in deal with contemporary economic issues in the modern world.

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