Biophysical limit and metabolic growth: New understanding of modern division of labor and sustainable economies

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1. Introduction

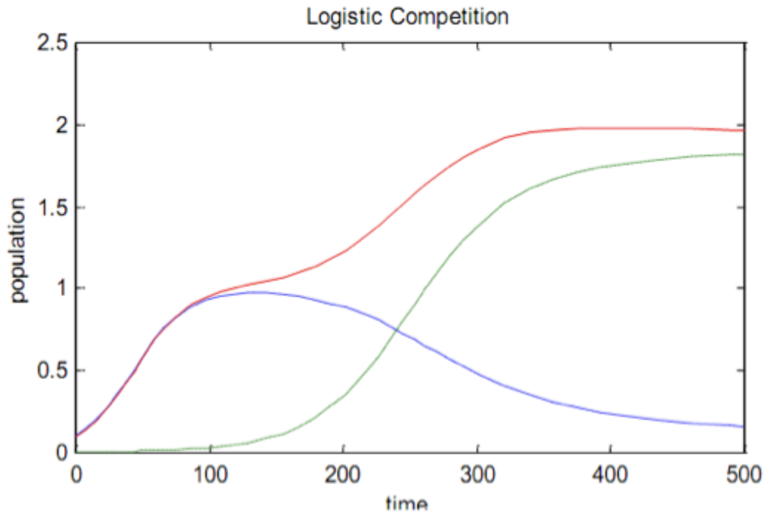
Current ecological crises are driven by excess consumption, which has been justified by neoclassical theories of unlimited growth. The theory of metabolic growth provides a better alternative to understand biophysical limits of economic growth and ecological constraints of the modern division of labor. It should be noted that among the founding tenets of classical economics is the Smith theorem that the division of labor is limited by market extent. Malthus, of course, whatever one thinks about the overall argument he provides, at least realized there could be competition between resources and population, and this issue subsequently influenced the works of Darwin and Marx. Today, economic "color chaos" provides strong support for Schumpeter's business cycle theory conceived as heartbeats, as well as Hayek's view of endogenous money. Furthermore, the nonlinear dynamics of the division of labor and the theory of metabolic growth reveal lifecycles (more exactly, wavelets) in the *co-evolution* of ecology-technology-culture. This allows a reconsideration of a "true face" of Smith in the form of a Smith Theorem of complex ecological systems or the trade-off between stability and complexity in which general equilibrium frameworks break down under increasing returns to scale. Clearly, given the predicaments of the modern period, coordination of nations is a more critical issue of the global division of labor than competing for power and wealth of nations. As such, it can be contended that Popper's theory on science philosophy should be brought to the fore in combination with complexity economics.

2. Neoclassical Theories of Unlimited Growth and Metabolic Growth Theory with Ecological Constraints

Two neoclassical growth theories on exogenous and endogenous growth provide theories for unlimited growth (Solow 1970; Romer 1986), and these promote excess consumption without appropriate recognition of biophysical limit. It is widely understood that mainstream economics cannot deal with the current ecological crises, including global heating, population explosion, and energy and food shortages.

In contrast, the theory of metabolic growth introduces a nonlinear network of population dynamics for limited economic growth (Chen 2014). The simplest ecological model of growth was the logistic model with an S-shape, which was verified in studies of the origin of the division of labor of social animals (Chen 1987). See Fig. 1.

Figure 1. The theory of metabolic growth and the Logistic wavelet.



The blue line represents obsolete technology or industry that declines into a logistic wavelet under strong competition from emerging technology (represented by the green line by a logistic growth curve with an S-shape). The envelope (red line) describes macro growth cycles as the sum of competing technologies at the meso level.

It can be argued that two classical theories shed new light on complexity economics, and these can be used to better understand the biophysics foundation of limited growth. The Smith Theorem clearly states that the "division of labor is limited by market extent" (Smith 1776, Book I, Chapter III; Stigler 1950). Malthus, meanwhile, draws attention to resource capacity as a constraint on population (Malthus 1798). Subsequent work develops a general Smith theorem or Smith-May-Chen theorem (May 1974; Chen 2014) based on nonlinear ecological networks rooted in population dynamics. Here, competing technologies are limited by three factors. First, resource capacity, (e.g., land or natural resources) which management science refers to as scale economy. Second, biodiversity, which indicates the scope of economy. Third, the magnitude of environmental fluctuations, such as natural disasters and wars. These provide aspects in which there is a trade-off between stability and complexity.

3. New Basics of Economic Ideas and Concepts

It can be argued that the theory of metabolic growth provides new foundations in economics based on five reasons. First, a biophysical foundation to economic growth introduces industrial structure into the economic framework. Technological competition mainly occurs at the meso (i.e. medium structure) level. Accordingly, the Keynesian micro-macro model can be extended into a three-level framework of micro-meso-macro economics. Here, the biological perspective is essential for meso-economics (Chen 2005). It is also the case that Schumpeter's view of business cycles, conceived as heartbeats, is fully supported by the discovery of economic "color chaos" and logistic wavelets in population dynamics (Schumpeter 1939; Chen 2010).

Second, the AK model of the neoclassical production function can be replaced by a dynamic model of evolving returns to scale. Any technology has a lifecycle with four stages: an infant R&D stage, an early or young stage of increasing returns, an adult stage of constant returns, and an aging stage of decreasing returns and subsequent death. This involves a changing role for governments and society. As Smith recognized "wealth is power" (Smith 1776, Book I. Chapter V). Accordingly, regulatory policy faces a critical choice: dominant economic power may protect obsolete technologies, while innovative sectors will demand institutional reform to advance rising technologies. How these are deal with provides for new understandings of economic justice and fair competition.

Third, as any ecological economist is aware, basic assumptions of neoclassical economics violate the biophysical foundation of economics. For example, the Arrow-Debreu general equilibrium model excludes increasing returns and the non-convex set, which is the typical feature of S-shape logistic growth with ecological constraints. Furthermore, the Lucas theory of rational expectations and micro-foundations is a slave model of population without individual degrees of freedom, and this is in tension with the principle of large numbers (Lucas 1972, Chen 2002). One might also note that the representative agent model in econometrics and finance is based on a random walk or Brownian motion model with a single particle, and this clearly does not accord with the behavior of humans as a social animal. The better alternative model of the financial market is a population model of the birth-death process, rather than variations on the Black-Scholes model of option pricing (Chen 2005). Market fluctuations are driving by gaming between bull and bear camps rather than random shocks of a representative agent. Insofar as this is achieved then it becomes possible to diagnose financial crises and provide an early warning (Tang and Chen 2014, 2015).

Fourth, the linear demand function with infinite wants cannot be justified by human nature of greedy. People's physical needs are limited by physiology, while psychological needs may be unlimited in some ways but are conditional (Maslow 1948). Moreover, modern diseases like obesity and diabetes are stimulated by the kind of conspicuous consumption long identified by original institutionalists (Veblen 1899) and anthropology can provide an alternative ecological perspective on civilization diversity and learning (Harris 1978; Gowdy 1997; Chen 1987, 2014).
Fifth and finally, the theory of metabolic growth can reveal the core mechanisms of colonialism and geopolitical conflict, which is rooted in market-share competition for energy and natural resources played out through the globalization of the international division of labor. Clearly, market exchange cannot solve persistent conflicts such as war in the Middle East (Coase 1960; Chen 2007). It is also notable that the idea that transaction costs tend to fall, proposed by Coase, is challenged by empirical evidence, since the U.S. economy *increased* its transaction costs from 25% of GDP in 1870 to 50% of GDP in 1970 (Wallis & North 1986). The point being made here, albeit briefly, is that international conflicts are ultimately ecological in nature and crisis prone. Coordination of nations is, therefore, more critical than market forces in dealing with global heating and ecological crises (Chen 2021, 2024).

4. Economic Complexity vs. Neoclassical Simplicity

Complexity science originated from astrophysics when Henri Poincaré discovered the three-body problem had no analytical solution in 1899. The discovery and development of deterministic chaos in the 1960s to 1990s found wide evidence that nonlinear deterministic systems only have limited predictability. Ilya Prigogine further recognized the important role of irreversibility in biological evolution since time's arrow and history inherent to biological evolution works against thermodynamics equilibrium. In reality non-stationarity is dominant in time series economics but absent in controlled experiments in physics and biology. In this sense economic complexity is *more* complex than physics and biology. In any case, the study of economic complexity reveals the fundamental flaws of neoclassical simplicity in three ways (Chen 2019, 2024).

First, the three-body problem is radically different from a one-body, two-body, and infinite-body problem. Three and many-body problems are more complex and often without analytical solutions, while in economics the representative agent model, the two-player model in game theory and international finance, and the mean-field model in statistics are all equivalent and deficient as an equilibrium framework. For example, a two-country exchange model can calculate the exchange rate and interest rate parity, but this is not so for three or more major currencies. This is also why the option-pricing model has a fundamental flaw since it is based on a single-particle model of Brownian motion without collective behavior.

Second, nonlinear stochastic processes may have a *multi-peak* distribution such that high moments cannot be ignored during phase transition, and this is the root of financial crises (a point that will make more sense to readers conversant in finance). The polarized presidential election in the U.S. shows a typical polarization with dual-peak distribution, which is a sign of bifurcation at the cross-point of coming crise.

Third, nonlinear trends in macro and financial indexes are the main difficulty in macro econometrics. So-called "market expectations" can be measured by macro trends separated by medium business cycles by the HP filter (Chen 1996). Yet macro management is better aimed at frequency rather than amplitude observation, and this is often used in medical diagnosis. Furthermore, the study of economic color chaos revives Schumpeter's view of business cycles as heartbeats.

Finally, the following six tables provide a summary of issues for interested readers and provide a comparison of different levels of complexity (Chen 2024).

Table 1. Simplicity and Complexity in Math Economics

Issue	Simplicity	Complexity
Number of players	One-body, two-body, infinite body	Three-body problem
Number of equilibriums	One	Multiple
Set theory	Convex	Non-convex
Returns to scale	Decreasing returns, constant returns	Increasing returns
Utility/Production	Unlimited, log-linear functions	Logistic functions
Deterministic	Linear	Nonlinear
Stochastic	Markovian	Non-Markovian
Time series	Stationary	Non-stationary
System	Close/Convergent	Open/Divergent
Boundary	No cell, no state	Multi-level boundaries
Structure	Homogeneous	Non-homogeneous

Table 2. Simplicity and Complexity in Economic Concepts

Concept	Simplicity	Complexity
Order	Optimization, convergence, stability Unique stable equilibrium	Evolution, diversity, uncertainty Multiple stable/unstable equilibrium states
Efficiency	Cost-minimization, predictability	Creativity, innovation, opportunity
	Infinite predictability	Finite predictability
Expectations	Rational, fully predictable Labor choice of recession	Nonlinear changing trends, open competition Interactions between trends & major players
Equilibrium	General equilibrium, disequilibrium	Non-equilibrium, multi-biological rhythms
Economics	Two-level of micro-macro	Three-level of micro-meso-macro
Money	Volume conservation Exogenous (independent central bank)	Volume expansion/contraction Endogenous (constraint central bank)
Policy	Invisible hands without policy	International competition & domestic change

Table 3. Simplicity and Complexity in Science

Discipline	Simplicity	Complexity
Math	Linear difference equation	Nonlinear differential & mixed eqn.
Systems	Linear system with single layer	Nonlinear system with trade-off between stability and complexity
Physics	Perfect, imperfect gas, fluid, solid Hamiltonian system Equilibrium structure Equilibrium thermodynamics Disorder=heat death Vector & Tensor field Harmonic waves	Nonlinear, non-equilibrium physics Dynamical system without optimization Dissipative structure Evolutionary thermodynamics Changing order out of chaos High-dimensional networks Non-Eucleadian wavelets
Chemistry	Linear chemical reactions,	Nonlinear chemical reactions
Biology	Biostatistics, game theory	Population dynamics, social animal
Psychology	Behavioral psychology	Evolutionary psychology
Neural science	Linearized neural cell	Brain structure and complex networks Hierarchical structures

Table 4. Neoclassical Simplicity and Pseudo-physics

Theory	Concept	Math	Pseudo-physics
Price	General equilibrium Unique price	Scalar field Linear pricing	Point state without time & space Infinite speed for price adjustment
Rationality	Preference	Isolated man	No social interact. & learning
Friction	Disequilibrium	Shocks	Frictions from struct. & boundaries
Crusoe	Individualism	Representative Agent	Selfish against nature of social animal
Optimal	Convergence	Equilibrium Order	Heat death=disorder= Maxim entropy in thermodynamics
Consumer	Greedy	DD& SS curve	Constraints of physiology & ecology
Firm	Transaction costs Complete market Perfect competition	Zero-transaction costs Perfect information No monopoly firms	Inertial motion, no changing speed Perpetual motion machine I. No classification of firms and consumers
Econometrics	Shocks	Random, Brownian	Perpetual motion machine II.
Finance	Arbitrage-free	Option pricing	Single particle without population
Exchange Rate	Bilateral parity	Parity theorem	Uncertainty in international competition
EMH	Efficiency	Random series	FD whitening filter for price signals
Rational	Expectations No financial crises	Error-free prediction	Infinite computing power Perpetual motion machine III

Table 5. Competing Models of Complexity

Classification	Theory / Model	Measure	Examples
Computation	Fractal, Levy	Fractal dimension	Coastline, geographic
System	Networks	Dimension, structure	Ecology, WWW, AI, big data
Physics	Sandpile, spin-glass	Scaling	Snowflake, turbulence,
Chemistry	Dissipative structure	Strange attractor	BZ reaction
Biology	Organism	Structure, life cycles	Species, cell, cell membrane
Sociology	Imitation, pandemics Traffic, city	Multi-peak distribution Flow structure	Ising model Two-fluid mode, city evolution
Economics	Color chaos, BD process	Correlations, trend High moments	HP filter, freeway model Phase transition of viable mkt
Brain	Epistemology Maslow hierarchy	Mind-structure Multi-layer needs	Piaget cognitive psychology
Computation	Fractal, Levy	Fractal dimension	Coastline, geographic
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Chemistry	Dissipative structure	Strange attractor	BZ reaction
Biology	Organism	Structure, life cycles	Species, cell, cell membrane

Table 6. Open Issues of Complexity Science

Concept	School	Theory	Examples
Self-organization	BAC	Dissipative structure	Origin of life, Division of labor,
Self-organization	SFI	Edge of chaos	ABM, artificial life, artificial market
Spontaneous order	Austrian	Holistic knowledge	Endogenous money without state
	Keynes	Wartime economy	Endogenous money with state
Biological clock	Schumpeter	Multiple waves	Business cycles like heartbeats
Scaling laws	EPS	Power laws	turbulent flow, high-frequency trade
Social temperature	EPS	Trade balance	Immigration through boundaries?

Note: BAC for Brussels-Austin-Chinese school, SFI for Santa Fe Institute, EPS for econophysics (Chen 2019, 2024).

5. Conclusion: Developing a General Theory of Physics-Biology-Economics

The development of complexity economics revives the dream of a general theory in economics, first proposed by Einstein in physics, and later suggested by Keynes in economics (Galbraith 1994; Chen 2024). It does so in conformity with the problem of biophysical limits rather than in ignorance or isolation from them. One might note that science has a hierarchical structure, and this is described in figure 2 below.

Figure 2. Hierarchical Structure for Symbolic System and Material World

Complexity

Brain Science

Psychology

Systems Economy

Biology

Math Chemistry

Physics

Simplicity Symbolic System Material World

(Left) The inverse pyramid of the symbolic system from simplicity to complexity.
(Right) The pyramid structure of the material world from bottom to top layer.

It can be argued that figure 2 speaks to a new understanding of philosophy of science. Physics is the very foundation of all scientific branches because organic life still obeys the laws of physics but is not explanatorily exhaustive. Clearly, a physics-biology approach ought to be a foundation of real-world economics and any grand unification theory should have a hierarchical knowledge structure. Mathematics meanwhile must be appropriate to its application.

Basic assumptions in the linear-equilibrium formulation of neoclassical economics are essentially utopian theories based on perpetual motion machines (Chen 2024). Ecological dynamics introduces nonlinear and non-equilibrium perspectives into ecological economics. Complexity sciences develop new tools for evolutionary economics and institutional economics with structural changes and diversified development. We need a new (Popperian) philosophy of science to understand the evolutionary tree of human knowledge. For example, the neoclassical model of efficient market is a special case of calm market while financial crise is the special regime of turbulent market in the phase-transition model based on birth-death process (Tang and Chen 2015). I contend that existing mainstream and heterodox economics can be better understood as special cases in different branches of the general evolutionary tree of human history.

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