A Complex System Theory of Economics

Sergio Focardi, PhD

In this paper we argue that any empirically faithful economic theory must take into account the complexity of modern economies. In particular, it must consider the relationship between the real and financial aspects of economies, it must consider that economies are not homogeneous but are divided into interacting sub-economies with different growth rates and different financial dynamics, evolve in quality and quantity and that products and services change continuously making it difficult to define and estimate inflation.

The notion that economies are complex systems is not new. The book *The Economy as an Evolving Complex System* , edited by Philip Anderson, Kenneth Arrow, and David Pines collects the proceedings of a seminar held in 1987 at The Santa Fe Institute on this issue. Books, papers and conferences that address the topic of economies as evolutionary complex systems followed. In this paper we discuss economics especially from the point of view of qualitative evolution and complexity of products and services. A key consequence is that no single number can capture economic evolution and that inflation can only be applied to economic subsystems. In fact, the complexity of products and the level of inequality reached by modern industrialized economies make it very difficult to capture the evolution of any modern economy with a single number.

In physics, Relativity theory has made it clear that the formulation of physical laws as well as physical measurements depend on the system of reference but we can still define invariants quantities and laws. The same dependence on the system of reference is true for Economics. However, while in physics the search for invariants proved extremely useful and successful, it is possible that no invariant can be found in economics.

The physical basis of economic growth

Why do economies grow? Economists assume that there is a positive return on capital. That is, economists assume as a given that it is possible to use a portion of the output to increase the stock of existing capital and that this increase, the Investment, combined with new discoveries and new technologies will increase in quantity or complexity the future output itself.

Set aside the problem, that we will discuss later, that it is impossible to define a quantity of output as well as a quantity of capital. Assume that we understand what is meant by the quantity of capital and the quantity of output. Let’s ask the question: what is the physical basis of this process of growth?

At least three main forces are at work. The first force is simply accumulation of permanent artifact such as houses or factories. If we use resources to build two factories instead of one later we can double the output. The second force is the ability to use tools to build better tools.

Primitive men created tools and then used the newly created tools to build better tools and thus improved their primitive output. The use of technology to build higher level technology has continued throughout history to the present time. Think, for example, to the software industry where software tools are routinely used to build better software tools. The third force is scientific and technological innovation. Scientific discoveries played a major role.

From the invention of the wheel, which was a major technology breakthrough, to modern electronics, product innovation and improvement in production is largely due to new knowledge. But we have to distinguish the process of improvement of current tools and technologies from the process of genuine scientific discoveries. The latter is unpredictable as it depends on the discovery of new laws of physics. For example, up to the 17^{th} century nobody could have guessed the development of electricity and telecommunications. Today, technologies such as teletransport are beyond our realistic imagination. They might or might not come true depending on true physical laws.

A mathematical model of the process of economic growth is probably too difficult to create. It is an aspect of what is called self-organization of complex systems. Complex systems are able to self-organize increasing their complexity and leading to emerging properties. Economies are an instance of self-organizing complex systems. However, a detailed mathematical description of this self-organization process is probably too difficult to create.

Some physical characteristics of this process are known. From a physical point of view the growth of economies corresponds to a decrease of entropy. This decrease of entropy is feasible because, from the physical point of view, economies are open systems that receive a net input of energy. Input of energy takes various forms including solar radiation, fossil fuels, nuclear fuels and so on. None of these sources of energy is inexhaustible, albeit with different time scales. While the sun might be considered, on a human time scale, a permanent source of energy, any fuel currently available is subject to depletion on a time scale which cannot be ignored.

Economists tend to think that the time scales of physical criticalities related to energy production are much longer than human scales. But this belief might be false. Tom Murphy, Professor of Physics at the University of California, calculates that if energy consumption keeps growing at a rate of 2.3% per year, well below historical records since 1650, the Earth surface will reach boiling temperature in 400 years and will irradiate as much heat as the Sun in 1500 years. This is not due to any climatic change but it is due to the basic thermodynamic effect that the only way for the Earth to cool down is through infrared radiation. See Prof Murphy's entertaining but chilling blog: http://physics.ucsd.edu/do-the-math/2012/04/economist-meets-physicist/.

Not everybody agrees that economic growth requires energy. For example, Tim Harford, who writes the Financial Times's "Undercover Economist" column, claims that there is a logical fault in the above reasoning, In his book *The Undercover Economist Strikes Back: How to Run or Ruin an Economy*, published by Riverhead Books, Harford claims that economic growth does not necessarily implies an increase in energy consumption. The economic value of a product or a service, Harford argues, is not necessarily related to the energy needed to create that product or service but is related to its desirability. He writes: “Here’s the logic lapse: energy growth is not the same as economic growth. GDP merely measures what people are willing to pay for, which is not necessarily connected to the use of energy, or any other physical resource.”

We can perhaps reformulate the problem in terms of complexity. Growth needs not be quantitative but can be qualitative, where qualitative growth means increase in complexity. This debate, points to a critical question in the theory of growth: What is the relationship between physical and economic growth? How do we link the two concepts in macroeconomics? From the ecological point of view it is crucial to understand if economic growth requires increased energy and raw material consumption. We can perhaps state the question differently asking if producing increasingly complex products requires more energy consumption.

In this paper, we have a more modest goal: How can we reformulate economics so that we can capture the diversity and quality of the output?.

The dual nature of mainstream economics

Mainstream economics has a dual nature. On one side, it is a theory of the physical working of modern economies, on the other side it is a monetary theory. It is useful to separate the two aspects. We can first define a purely monetary theory of economy. Actually, the quite smooth growth of modern economies is largely due to the monetary aspects of economies. The idea of a purely monetary economy is not new. Sir Ralph George Hawtrey proposed in his 1929 *The monetary theory of the trade cycle* an explanation of business cycles purely based on money flows.

In order to study a purely monetary theory, we can start from the structuring of economies in firms, wage earners and capitalists, plus government and a banking system. As a first approximation, we can ignore exchanges with foreign countries, as the total balance of in/out flow of money is small. Firms pay out wages and dividends and make investments using retained earnings. After some lag that simulates production processes, firms collect wages plus debts incurred by wage earners and collect additional money from sales to capitalists.

A complete stock-flow consistent model of a purely monetary economy can be created and simulated. A model of this type would simply follow the flow of money. The key assumptions that needs to be made is that firms pay wages, that wage earners take on an increasing amount of debt, that wage earners and capitalists return the money to firms buying products and services. We can add an asset market and simulate also the flow of money to assets.

However, to make a purely monetary economy realistic we need a number of additional assumptions and equations. We need to make assumptions about a population growth, about the growth of people's debts and investments. How can we realistically make these assumptions? Mainstream economics answers that we need a theory of the real economy. The key component of mainstream theory of a real economy is the production function that links production factors such as capital and labor to the quantity of output.

But a model of the real economy is an idealization that does not model anything real. In his book *The Origin of Wealth* Eric Beinocker estimates that the output of a modern economy is formed by tens of billions of different products and services. In addition, a large share of products and services change continuously. There is no way we can aggregate output quantitatively. And there is no way we can aggregate capital quantitatively. We have to accept that we can, albeit with uncertainty and difficulty, measure the market value of the output of an economy, but we cannot say that this output corresponds to a well defined *quantity* of physical output. A monetary value of output can correspond to many different sets of physical output.

In a modern complex, evolving economy measuring with a single number the quantity of output or the quantity of capital is impossible. Economists and mathematicians have tried to solve the problem by measuring changes of output or capital as opposed to measuring output or capital themselves. The reasoning is the following. Even if the output is made by heterogeneous products it can be broken down in sets of products that are homogeneous. For each of these sets, we can define meaningfully a percentage change. For example, we cannot mix cars and cruises but we can measure the increase in car production and the increase in cruise offerings.

This expedient would seem to solve the problem as we have replaced heterogeneous quantities with homogeneous dimensionless percentages. It remains only to attribute a weight to each rate of change so that we can average. Now, for averaging purposes, it seems reasonable to use the relative market weight of products and services. In a nutshell, this is the basics of the theory of indexes.

But there are two problems. First, it is well known that no index, that is, no averaging method, can be considered the true index. It has been demonstrated that no index can satisfy a set of basic criteria. This makes indexes somewhat arbitrary. Economic theory would ultimately depend on the choice of indexes. But there is a more serious problem. In modern economies products and services change continuously. New products and services come to the market and old ones disappear. Even if we solve the problem of heterogeneous quantities, we are left with the problem of qualities.

We are so used to idea of quantitative growth that these considerations might seem artificial. But they are not. We pretend to capture with a single number a process of innovation and growth that involves the changes both in qualities and quantities of a staggering number of products and services. Impossible, or better, arbitrary.

Ultimately, the faith in the ability to measure the quantity of output rests on the fact that our key unit of measure is money. But we know that prices are relative prices so that value is defined up to a multiplicative constant. The usual answer is discounting output by an inflation indicator. The measurement of inflation is the measurement of the change of value of a panel of goods that do not change in the period when inflation is measured. This measurement is partial, it can be applied only to some segments of the economy. Other segments escape inflation measurement because they change too much and too fast.

Therefore we are back to the original problem. A purely monetary economy seems to be the answer as it uses only true measurable quantities, that is money value. But a purely monetary economy still needs relationships and equations that link the monetary value of capital and output. And these relationships must take into account the real economy.

Can we define a model of the real economy that takes into account both quantitative and qualitative changes?

There is probably no simple answer to the above problem. Discussing an answer involves deep methodological issues. A modern sophisticated answer to the problem of creating a new empirically faithful Economics comes from multi-agent systems. Multi-agent systems solve the problem of complexity upfront by creating theoretical models, implemented as computer programs, which have a level of complexity comparable to that of the economy they want to simulate.

Complexity, interactions, innovation are all taken into account upfront by computer models formed by thousands of interacting entities. There are of course serious implementation issues. The number of parameters involved makes the problem of calibration to real data extremely difficult. Multi-agent system are highly chaotic systems. The design of these systems must include constraints to avoid explosive, uncontrollable behavior.

Assuming these issues can be addressed, multi-agent systems are very useful to conduct numerical experiments. One can simulate scenarios that it would be impossible to create in reality. However, multi-agent systems are not theories, or perhaps they are theories in a different sense. A theory should be a parsimonious representation of phenomena, but multi-agent systems are not parsimonious.

The theory of complex systems is an array of theories that consider different aspects of complexity, from self-organization to network theory. Some aspects of complex systems have been analyzed in depth and rigorous mathematical results as well as computer simulations are available. To mention a few results, the theory of random structures, from random graphs to scale-free networks is well known. The emergence of power laws, another key aspect of complexity has been analyzed in depth. Interacting particle systems are also well known mathematical structures.

Self-organization, one of the most fascinating aspects of complexity, is still a science in the making. How does it happen that structures formed by interacting particles self-organize so to show emergent properties? And what are the limits of this process? Can macroscopic properties be analyzed in terms of microscopic behavior? Or do we reach the limits of computational complexity so that macro behavior is not computable from the interaction of microelements? These are crucial questions for many sciences of complex systems from biology to economics.

In this short paper we intend to discuss methodological issues. Let's go back to the previous question: Can we really understand a monetary economy? How can we complete a monetary economy? Monetary aggregates are operationally defined quantities. With enormous practical difficulties, we can compute the nominal GDP or the nominal GNP and we can compute the value of investments. We can compute the wage bill and we can compute statistics on the amount of global credit or the size of the money mass.

How can we complete monetary equations? We cannot define and compute physical aggregates such as the quantity of physical output of an economy. These quantities do not make sense. Textbooks of macroeconomics bypass the problem assuming an economy produces one good or a composite good. But it is well known that these quantities are not real measurable quantities.

Can we take a more scientific approach? The famous physicist Sir Arthur Stanley Eddington once wrote that:

> *We have found that where science has progressed the farthest, the mind has but regained from nature that which the mind put into nature*.

The meaning of this quote is that we cannot impose our image of reality on the real world. Economists have to abandon the notion that economic theory is descriptive of reality. This idea was already put forward by Milton Friedmann in his 1953 *Essays on Positive Economics*. Models are not descriptive of reality. As observed by the great philosopher and logician Willard Van Orman Quine, theories respond *in toto* to observation. Some variables are operationally defined, others are defined implicitly through the theory.

The notion of a quantitative output of an economy or the quantity of capital are simply not observable. What we can do is to identify and clearly define operationally those quantities that we can observe. For example, the inflation rate is not the percentage change of a price level, which does not exist, but it is the change in value of a basket of products that remain constant for a while. This is a measurable quantity but it does not have the meaning of an economy-wide change in price level usually associated to the term inflation.

If we want to create a parsimonious macroeconomic theory we have to collect observables and connect them with hidden variables whose meaning is to connect observables. Perhaps the best example of this process in the physical science is the notion of information. In a scientific term, information is not what we mean in daily language. It is a precise scientific term linked to theory.

Therefore, what is the meaning of a production function? A production function, provided it is useful, it is a function that links the value of capital and the amount of labor to the value of output. Whether such a function exists or not is an empirical question. And we have to resist the temptation to think that it represents a true or perhaps approximate relationship between the amount of capital and the amount of output. These concepts simply do not exist.

If we want to introduce the idea of qualitative changes in a parsimonious model, we can introduce two output variables, Quantity and Quality, and link them to the nominal output by a pricing relationship. And we can link Quantity and Quality to the amount of capital.

If we take this approach, we should keep in mind that variables such as Quantity and Quality are not directly observable. They are parameters that allow to link observable quantities such as the value of GDP and the value of capital. We can say they are two parameters that characterize an economy. Of course, defining two hidden variable and a relationship does not add much to our knowledge. We need to link these variables to something else, for example some measure of the complexity of products.

This is only a sketch of a methodology that we often find in physics: we define abstract variables that link observables. Electromagnetic fields, for example, are abstract variable that we assume describe a field which we ultimately observe only through its effects in different domains such as mechanics.

If we want to reformulate Economics in such a way that it is both empirically faithful and that it takes into account innovation and complexity we must follow the same principles of physics and avoid to insist that all economic variables have an interpretation. Models connect observation, anything important should be related to observables. Hidden variables might be mathematically and conceptually useful but they might lack interpretation.