Complexity Science and 21st Century Issues

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"Where does wealth come from? A Complexity Economics Perspective"

One of the most stunning facts in economics is the explosive growth in worldwide wealth over the past 250 years, and the related growth in the complexity of the global economy. Conventional, particularly neoclassical, economic theories have a difficult time explaining this pattern of growth. The talk explores what complexity science might offer in explaining this puzzle; most notably from an evolutionary theory perspective.

The question I'm going to look at is a very fundamental one: 'how is wealth or economic value created?' I'm going to start with some facts and ask what kind of phenomenon we are dealing with. Then we'll go from that characterisation to a discussion of evolution in the economic context and a possible theory of economic value.

Number one empirical fact is that there is a global economy and this is something that often gets short shrift in economics. Economic historians sometimes look at institutional economics, but in the mathematical heartland of mainstream economics this question usually doesn't get much attention. It is, when you think about it, the most complex human creation. We can think of other human made complex systems such as the space shuttle, or institutions like the Catholic Church or the Inland Revenue, but the global economy outweighs them all. Economics does not have a good theory about how it happened and explaining its origin in classical economics is a bit like trying to understand biology without having a theory of the origin of life.

Empirical fact number two is if we look at economic growth over time, particularly over long periods of time, a lot of people intuitively think of it as some steady process or maybe an exponential process. The first tools were made by Homo habilis about 2.5 million years ago and one of the ways of defining the birth of an economy is by the production of artefacts because they were undoubtedly traded. Admittedly we don't have any statistics from the days of Homo habilis, but researchers at Berkeley have done some interesting work putting together data from anthropologists. If we look at how GDP (gross domestic product) per capita has grown since then we can see that for a very, very, very long time not much happened. However if we zoom in at about 15000 BC we see a big leap, and if we zoom in to roughly 1700 up to the present, all hell breaks. This isn't just exponential, it is more than exponential and actually double exponential. Statistics show that almost all the wealth in human history has been created in the last 0.03% of time. So it's an extremely explosive pattern of growth. We know that the Industrial Revolution happened circa 1750 and we know lots of historical facts but we don't have a theory that can explain the phenomenon.

Empirical fact number three is also something which hasn't had much attention in the economic literature and that is the growth of diversity in the economy. The term SKU (stock keeping units) is taken from the retail trade and is essentially a

measure of how many types of artefacts you have. So for example WalMart would count how many different types of jeans and types of power tools etc and come up with this measure. It might be that WalMart has 100,000 SKUs and anthropologists have given us data on how much stuff hunter gatherers had. It appears a tribe had roughly between 100 and 1000 different types of things. Just for fun I spent some time with the Masai tribe and actually counted the number of things in the Masai village. It came out to about 450 so that's a relatively small number. In a place like London or New York however, just counting bar codes, it's about 10^{10} things. Wal-Mart has 100,000 different items, there are 200 different channels on cable TV and 127 different kinds of mosquito spray on the market. So in a relatively short period of time, human society has produced an enormous increase in the diversity of the economy.

What kind of system are we dealing with here? Growth theory addresses some of the issues, but nothing in the standard text books on micro or macro economic theory accounts for it. The chief reason for this inability is the assumption that basically the economy is a closed equilibrium system, and as our physicist friends will tell us, such systems cannot, by definition create spontaneous order or produce the kind of explosive growth pattern and diversity. So we must ask the question: 'why do economists think that the economy is an equilibrium system?' Equilibrium analysis is very useful in certain contexts and a very powerful tool, but it doesn't seem that anybody looked around and said, 'That looks like an equilibrium system'. Economic historian, Phil Marowski (?) has done some detailed research and claims that the reason why economics is looked at in this way is essentially an accident of history.

The concept of an economic system as an equilibrium was introduced in the 1860s or 1870s by Walras and Jevans (?) and it seems these ideas came from physics which was at a point when statistical mechanics and equilibrium theory were in the texts books. Walras was looking for some mathematical rigour in economics, since it had previously been essentially a philosophical subject, and he copied a set of equations and techniques straight out of the text books. These became a theory for economic systems and Jevans later did the same thing. This also happened at a time in physics when the First Law of thermodynamics (conservation of energy) had been developed and the Second Law was in the process of being worked out, but not yet in the textbooks. So in economics there was a notion of equilibrium but no notion of entropy and specifically no mention of open systems. Economists therefore took this pre-Second Law type framework and ever since then have used equilibrium analysis. These days a physicist looking at the economy would think it obvious that it is a thermodynamically open system in a very real physical sense. Looking back at some of the older economics literature there was quite a lot of talk about flow and energy but once you get to Walras and beyond, it fades away.

Nevertheless the economy actually lives on a huge input of energy which fuels a decrease in entropy as order is increased in the system and at the same time as we get these emergent patterns there is an increase or export of entropy back out of the system through pollution, heat and waste. To physicists, thinking of the economy in physical terms, this is pretty straightforward stuff, but it's been lost in economics literature and in fact there have been some negative views put forward. It has been said that talking of entropy in an economics context is a sign of 'either a crank or a half baked speculator'. Well, a couple of cranks and half baked speculators actually understood these ideas long ago. Schumpeter talked about the need in economic theory to account for novelty creation; something which was missing in neo-classical

economics, and hence his famous quote that you can add 'as many coaches as you please, you will never a railway get thereby'.

Another interesting figure who understood the economy as fundamentally an open thermodynamic system was the Rumanian economist Chechesky Roagin (?). Apart from being a very good neo-classical economist (Sandelson called him an economist's economist before he went off the rails), Roagin wrote that: 'casual observations suffice now to prove that our whole economic life feeds on low entropy'. The overwhelming characteristic of the economy is entropy fighting and order increasing. Fortunately for some time now there have been a number of people outside the neo-classical tenure talking about this approach.

So to sum what I have said so far, the most striking feature of the economy is this local decreasing entropy. It is also an open thermodynamic system and we need some kind of mathematical theory to account for it that doesn't exist in traditional economics theory. Evolution is one process or algorithm that we know reliably decreases local entropy and creates order. That leads us to ask questions about what kind of evolutionary theory we might apply in economics to account for order creation and again there's a long history of evolutionary ideas in economics going right back to Darwin. Darwin borrowed ideas from Malthus and various metaphors right up to a modern (communist ?) one represented by Nelson Winner have been used. The fundamental limitation of this approach is that it is driven by metaphors from biology which makes people look for the economical equivalent of genes and generations of transmission mechanisms etc. So the danger is that a lot of this work makes the same mistake that Walras and Jevans made in using a metaphor borrowed from physics. The question we should perhaps be asking is: 'what is the universal class of phenomena that we're dealing with and what are the specific instances of the phenomenon?'

Now at places like the Santa Fe Institute (SFI) there are a number of computational views of evolution and a lot of work has been done showing that evolution is a much more general class of system than biological ones. There's that wonderful SFI book by Crutchfield (?) and Schuster which, instead of looking at evolution as a biological system and trying to find an algorithm, suggests we look at it in a very generic universal computational way and then ask whether there's something to describe economics out of that.

What is a computational view of evolution? Well, what we're really looking for is an algorithm for design. In other words a model of a process that creates order and structure in the face of constraints, and to illustrate that there's some very nice work by Ralph Simms who built a world on the computer made of little blocks with different body segments. Using a DNA type code and a typical genetic algorithm set-up he then evolved his block creatures in the face of several different sets of constraints and fitness functions. One of the fitness functions was that his blocks had to swim so he created the physics of moving in water and then gave the creatures a test to see who would be the fastest swimmer and then reproduced those in an evolutionary process. Given the constraints of the physics of water and a fitness function of the fastest swimming time, out of a random soup of block designs emerged things with tails like snakes and things with fins and flippers etc.

With no intelligence pre-built in, the simple operation of the evolutionary algorithm under the given constraints gave rise to some sophisticated forms. When he changed the constraints to moving in air and the fitness function to walking on land under gravity he got crab-like things with legs and so on. Evolution, we may conclude, is an algorithm for finding 'fit' solutions in an enormous design space. If

we think of the combinatorial number of possible designs you can make out of a set of blocks even with a finite set of blocks, it's huge and evolution is the way of finding the fit designs in that huge search space.

Putting this in a more economic context how can we think of finding fit designs? One way is to turn to game theory and we're probably all familiar with the Axelrod example, called The Prisoner's Dilemma, where you have two prisoners developing strategies in playing against each other. Axelrod was followed by some people like Christian Wingrin (?) who applied evolutionary algorithms to finding fit designs for playing the Prisoner's Dilemma. This essentially involved having a space of all possible strategies and finding fit ones within that design space and what we see in these experiments is a creation of order and lower entropy. Starting with a lattice of agents represented by squares, each agent plays the Prisoners Dilemma with his neighbours. From simple 'tit for tat' strategies the evolutionary algorithm builds increasing complexity. In essence it's an ecosystem with 'fit' strategies surviving to dominate and if the activity had involved the production of artefacts, such SKUs would have shown a spontaneous growth over time.

The Prisoner's Dilemma is an extremely simple game, but it gets us thinking of design in the context of the extremely complex game of the economy. If we go back to a generic computational view of evolution, like the work done by John Holland in the 1970s and the SFI people, a fairly robust way of looking at this has built up. In order for evolution to work you need some basic mechanisms, but the first thing you need is a design space so you can understand what it is you're searching in. Then you need a schema; some way of representing that space in digital form so that you can process information on the designs. Thirdly you need a 'schema reader', something that can translate schema code from the theoretical design to an object that interacts with the environment. I'll explain this in a moment. And then finally you need to feed the designs back into the evolutionary process.

An important thing to note about the idea of a schema reader/builder is something the philosopher, Daniel Dennett made clear and that is that the schema will never fully incorporate all of the information in the design. In the case of biological evolution there's a temptation to think of DNA as a blueprint that contains all the code to build say a chicken. It actually doesn't have anything close to that amount of information in it and Dennett refers to the movie Jurassic Park as an illustration of the flaw. In the movie, a mosquito preserved in amber is found to have dinosaur DNA in it which is used to create a living animal. Dennett says that this can never happen because in order to create a dinosaur out of dinosaur DNA, you need a dinosaur DNA reader. And if we ask what that is the answer is a female dinosaur with an egg reading mechanism. She is the only thing that can take the schema and turn it into physical reality and a huge amount of information passing and processing has to go on.

If we take the generic computational perspective we can start to think how we can translate this into an economic context. Again in thinking about the design space for the economy there's a useful metaphor from Dennett which is his imagined design space for all possible human literature. Is there, Dennett asks, such a thing as a design space for all the novels, stories, poems and non fiction books that ever have been or could be written? He says in theory there is. You have 100 (?)characters in English and if you take all possible ways in which those can be arranged you have 100 million books. If you take one page of roughly 2000 character spaces, a 500 page book has a million character spaces so there are only 100 million books that can ever be written. Of course you might say 500 pages is an arbitrary limit it's still fortunately an

extremely large number and we couldn't get through all that design space in the lifetime of the universe.

But the point is that though we can take what appears to be an extremely complicated design space and bound it in some finite way, it turns out that though some design spaces are finite at some point of time, they can be unboundable because they grow. And that's because the schema reader itself evolves over time. The longest book ever written is by Proust. It's about thirteen volumes, but there's a practical limit to how much a person can put into a book. I mean nobody wants to read a book that's twenty volumes long and that puts a kind of bound on design space. But if you imagine in the future we had chips in our brains then the design space of possible books may expand. Just as in the biological world the schema readers of cell biology change the design space of DNA.

We can take this idea of design space for literature and think about it in economics. What is a design or schema in an economic context? It's a business plan. And the way we encode the plan in strategic language and charts and pictures, diagrams and tables and so on, can all be digitised. We can think of it as a sub-set in Dennett's literature design space. In that sub-set is the business plan for IBM today and the business plan for ten years time, and the business plan for a hunter gatherer tribe in five thousand BC and so on. We can think of the design space of all possible business plans. And if we think about what's inside a typical strategy there's usually some statement about the market environment, some statement of product operations, some statement of future development and so on. There's the notion of trying to find a strategy which is fit for a particular environment and we can think of each business plan as an experiment in some design space of all possible business plans.

If I borrow some terminology from Dick Nelson of Columbia University I'll say that we need a 'description of physical technologies that tell us how we're going to carry out that strategy in terms of the products and services we can make' and also 'a set of social technologies', in other words how we organise people to achieve it. We can think of the physical technologies and social technologies and statements of strategies as being the building blocks and the schema could be combination and recombination. So I might have a social technology for 'just in time' inventory management system and that could be part of any number of business plans which could be combined into any number of contexts.

Just to give you an example of how the business plan is a form of design. If you take Border's book store, the strategy would be statements about relative size of business, how much of the market they could hope to gain, where to put the retail outlets and so on. It would have a set of specific technologies for organising the people in the system in terms of the logistics, how the books are deployed and carried around etc. Then there's a set of physical technologies for store design, computers, warehousing etc. And if you take a company like INTEL then it would also have statement of strategy and a set of physical and social technologies which describe it. Of course business plans are not all written down, but you can imagine a group of MBA graduates going in and capturing these things in some kind of document.

In principle all designs can be coded into some kind of schema. They may be dispersed around the organisation as lots of different documents and in people's heads, but there is a design. So if you think of the design space of all possible business plans then economic evolution is a search through that design space for business plans fit for a particular environment. What's the reader/builder? Well it's people as the management team. The schema reader for IBM is IBM's management team, and just as in biology the schema/reader evolves with the schema itself, so a

business plan for IBM would be a document that the management team could read and understand, take action on and effect some change and adapt in the environment. There's also co-evolution going on which means an IBM strategy wouldn't be much good for a South American hunting party and vice versa.

If economic evolution is a search for fit business plans in the design space of possible business plans a question to ask is: 'what's the role of rationality in this?' Business plans are not just designed by natural evolution but by people. A management team sits down and thinks about it and tries to come up with rational ways of designing the business. But we tend to have an illusion about the rationality. We tend to think that engineers sit down and come up with say the optimal design for a bicycle whereas what is really going on is what I call deductive tinkering. We try to understand things and come up with designs, but they have to be tried out in the environment to see if they work and any engineer knows that you take your best shot as the deductive part and then there's a whole lot of tinkering and trying things and getting feedback and experimenting along the way.

The role of rationality in this search for business designs is that it feeds diversity into the system and the same kind of tinkering that goes on with physical artefacts goes on with business plans. In formal terms the tinkering feeds the evolutionary algorithm with diversity and the rationality preserves the integrity. It's different from the diversity of a random evolutionary process but it is still a source of diversity. In an economic context we can think of a search for fit business plans as going on at different levels in a selection and amplification process. First there is the individual mind of a manager at IBM who has a plan and tinkers away with different ideas. Then the same process will be gone through with other executives who cross things out and combine and recombine the modules until they find something that they think will work. Then these plans get expressed in the environment in terms of actions. In other words, investments are made, people are hired and fired, products are made etc. Finally the market goes through its own selection process and again it's different from the biological context in which there are not the same levels. Nevertheless from a computational view it's still a process of creating diversity and selection and amplifying the strategies that succeed.

What I'm saying is that we can start from a generic computational notion of evolution and begin to translate some of these ideas into an economic context. If the economy is characterised as a search for economic activity through business plans we can consider these as designs. This creates an opportunity to think differently about the whole notion of economic value. And if we ask what that value is, one of the things that jumps out of the three facts I showed you earlier is that there seems to be a relationship between wealth and complexity and between wealth and order. This suggests a relationship between our notion of wealth and our notion of order and low entropy. I'm not the first person to note that. Chechesky Roagin (?) noted this in 1971 in two statements that identified two fundamental laws of economics which may be the only two fundamental laws that we know.

When economists usually talk about 'fundamental laws' such as 'supply and demand' these are actually approximations rather than fundamental laws. But Roagin offered statements about regularities in economic systems for which there are no known exceptions. The first is that all valid transformations and transactions are thermodynamically irreversible and Roagin's epithet is 'that you can't burn the same lump of coal twice'. In other words the activity of creating economic value inherently involves irreversible processes.

The second is that all value-creating economic transformations or transactions are entropy reducing within the economic system and again there's a fundamental relationship between value and wealth creation. Someone suggested that there might be value-creating transactions or transformations that are entropy increasing, like making the bomb or destroying a building for reconstruction. Well, making the bomb is order in design and construction so presumably a decrease in entropy and setting it off an increase in entropy though perhaps only the Defence Department would see it as value creating. Of course demolishing a building is just an intermediate step if there's going to be a reconstruction. It's a bit like eating a hamburger in which you break down the cow protein in order to build it into yourself.

Nevertheless the two statements provide a starting point for thinking about the connection between thermodynamics and economic value creation. If you look at this from an evolutionary perspective the most fundamental constraint is the Second Law of Thermodynamics. We can think of wealth creation as a version of 'fit' order. Its activity lowers entropy and creates an order which is in some ways fit for some environment. That fitness function is changing all the time and is contingent just as it is in biological systems but economic evolution creates things which are ordered though they may be increasingly complex.

Questioner 1: I was interested earlier in this idea in business that 'no surprises' is a kind of motto, though holding innovation workshops should lead to good surprises. A lot depends on the economic climate. In other words whether there's enough money to play around. You mention diversity and I would like to ask whether it is your experience that the economic climate impinges on the integration and frequency with which this requisite diversity is used in organisations?

Answer: I think you'll find most organisations are diversity challenged. That diversity requirement does not always appear in business plans and part of the reason for that is that operations or processes to do with transactions and production usually require a reduction in diversity. In other words efficient operations usually require a funnelling down of diversity whereas evolution requires a source of diversity, which is why we see a lot of ill adapted organisations in the literature. Most economic evolution seems to happen at the market level rather than within organisations and there's a greater diversity of business plans at the marketing level.

Questioner 2: (Can you build a paradigm?) of an optimal market from a neo-classical economics point of view (?)

Answer 2; If you ask a neo-classical economist the question; 'why do you like markets?', the answer is 'allocated efficiency' (?). If you ask the question from an evolutionary perspective 'why are markets as they are?' then they tend to say the fitness function reflects the needs of society which is slightly different. It's not about allocation but rather that the fitness function is driving the process of diversity, selection and amplification. That drive is a reflection of the tastes, needs and wants of society. Yet the other alternative for organising the economic system is what anthropologists call 'big man' society which results in a hierarchy. Evolution still goes on in these types of 'command and control' system in the form of diversity of business plans but the fitness function is the happiness of the big man or woman. Markets as a way of organising society are valuable or a good thing if they reflect the needs of society as a whole.

Questioner 3: Is there a fundamental economic and social reason why an increasing diversity and complexity is necessarily accompanied by a decrease in entropy?

Answer: What's the fundamental reason for a decrease? Well, when we think about economic activity at a basic level it's that of humans going around trying to fulfil their needs. Take Homo erectus banging a couple of rocks together. He has some need, say to skin an animal, so he's taking things in his world and ordering them in order to meet his needs. And at the end of the day that's what economic activity is about. It's an activity to meet human needs. But we can't just rely on rationality alone to predict what kind of order we need and that's why it's an evolutionary process going on. We try things that might or might not meet our needs and figure out which one works and which one doesn't. As that process of tinkering goes on entropy goes down.

Questioner 3: Why do you use a physics analogy. I'm not sure that it applies.

Answer: Well it's not just an analogy, it's a real physical phenomena. Entropy has to be measured relative to something. An automobile is a relatively low probability state of the particles that make it up.

Questioner 4: Well entropy doesn't always go up. Even in physical systems, if they're sufficiently small, you can have fluctuations and you can get more ordered states. But the reason that you have the Second Law at all is that it is more likely that you have disordered states than ordered states and so if you have a really big system it becomes overwhelmingly like that. So in practical terms entropy always goes up. Now the reasoning for getting the increased likelihood of disordered states is simple. It's much easier to mess your room up than it is to clean your room. There may be a million ways to mess it up and only a few ways to clean it.

Questioner 3: It's not in the logic. I see life as an increasing order. An increase in entropy is biology. An increasing order is economics. Kauffman says in his latest book that probably the Second Order of Thermodynamics does not apply in economic and biological systems.

Questioner 4; I think to be fair to Kauffman that ultimately he says that entropy does increase but in a local environment there is a decrease.

Answer: Well one of the things that comes out of this is that you can't go back on economic activity because of pollution and global warming etc. All this work creating activity is decreasing order and increasing entropy outside of the economics system.