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Energy Flow, Emergent Complexity, and Collapse

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This is a guest post by George Mobus, who is an Associate Professor of Computing and Software Systems at the University of Washington Tacoma.

Civilizations grow in complexity given the right circumstances. And all too often they end up collapsing. History is replete with examples. Joseph Tainter, among others, has examined collapse from the standpoint of decreasing marginal return on investment in increasing complexity, which he posits is the most common factor in collapsed societies. The key question one must ask is: What critical circumstance (if there is one factor above all others) enables a society to grow in complexity in the first place? If we find an answer to that question we may also find what causes the decrease in marginal returns as complexity increases. This is certainly a growing concern for our modern civilizations. I advance a systems theoretical and principled thesis, below, that puts the increased flow of energy as the key enabler of increases in complexity. And I examine what we might expect from declines in that flow rate when sources are depleted.

Joseph A. Tainter's The Collapse of Complex Societies

If you haven't read Tainter's 1988 (some would say prescient) book, The Collapse of Complex Societies (Cambridge University Press), or if you haven't read it recently, you would do well to do so at your earliest convenience. [Also see a speech he gave the 94th Annual Meeting of Ecological Society of America, posted on The Oil Drum, here.]

I had the great good fortune to meet Joe at the Second Annual Biophysical Economics Meeting in Syracuse, NY this last October. He came to give the plenary talk in which he connected energy return on energy investment with his theory of how evolving complexity in societies figures into collapses, when they occur. I then stopped over in Logan Utah on my way home to Washington state and spent some quality time talking with him that evening over a single malt scotch (a label I had never heard of before - very smokey!)

So I thought I'd dig out my copy of Collapse when I got home and re-read it. I remembered not being quite as interested in the details of Roman and Mayan societies in the way an archeologist would be (Joe's credentials) and had probably skimmed too much. His lecture at Syracuse piqued my interest now that I know a bit more about what seems to be going on in our modern societies in the post-peak oil world. Much to my chagrin I couldn't find my copy. Actually I vaguely remembered having borrowed it from the library (I wasn't rich enough in 1988 to have much of a personal library), so I quickly got it from Amazon, along with a few other classics on the topic, and read it again. This time with more informed, if not fresher eyes.

Joe's thesis boils down to this: Societies evolve greater organizational and technical complexity to solve social problems that arise due to external forces or population pressures or overuse of natural resources, etc., and at some point, the marginal beneficial returns (problems solved) begin to decline leading to lowered margins of error for dealing with possible catastrophic impacts. Societies collapse when increasing complexity no longer has a payoff and something else bad happens.

As I read this anew I thought about other areas that I have been developing some expertise in, namely the evolution of complexity in dynamical systems (from general systems science) under the influence of the flow of high potential energy. I felt inspired to write more about that since I think there are some general principles that we could use to decipher what is going on in the world today and have some sense of what to expect from tomorrow.

Energy Flow and the Evolution of Internal Complexity

The term complexity has become somewhat problematic over the last several decades because of the difficulty researchers and authors have had in coming to some kind of consensus on its meaning. Of course it is like pornography, right? We know it when we see it. I have attempted to provide a more concrete treatment of the subjects of complexity and its evolution elsewhere, so I won't go into that in detail here. Readers who want a more precise definition should take a look at those works. For our purposes a brief summary follows.

There are really two kinds of complexity, potential and realized. Potential complexity comes from the *a priori* existence in a semi-closed system of myriad raw components, both in absolute numbers and in types. Types, here, refers to components that have different personalities or interaction potentials with other component types. The more different types and interaction potentials there are, the more realized complexity might obtain within the boundaries of the system.

Realized complexity is what most of us think about when we come across something that already has organization and appears to be functioning through myriad actual interactions among the components. When we see multiple kinds of arrangements of components that appear to be regular and strongly interacting, we apprehend the system as complex. We can view a system from outside, say when we run into a complex piece of machinery (perhaps looking inside to see the workings), or from the inside, as when we try to grasp the complex nature of our own society. Either way, realized complexity is characterized by organization, stability of interactions, many kinds of interactions and often recognizable subsystems, which may be, themselves, complex. A good example of a complex system with complex subsystems is a living cell, especially a protist such as a Paramecium.

A central question of the evolution of organization asks: How does an unorganized collection of components (potential complexity) actually develop over time into an organized, functioning (realized complexity) system?

This question lies at the heart of the still somewhat mysterious (though not mystical) issue of the origin of life on Earth. Life emerged from non-living components perhaps some 2 to 3 billion years ago. And once the basic formula of complex metabolism in cells developed, life proceeded to evolve further, eventually producing simple multi-cellular organisms, and then, in a much shorter time frame, to us.

Harold Morowitz (*Energy Flow in Biology*, 1968, Academic Press), following closely on the heels of Erwin Schrödinger, who famously asked the seminal question, "What is life?", provided an important insight into the nature of evolution of organization in semi-closed systems. He demonstrated that when energy of the right kind flows from a source of high potential, through the system, and exits at a lower potential (heat), that work is accomplished within the component milieu and structures obtain. He coined the phrase made famous by Stuart Brand on the back cover of the Last Whole Earth Catalog, below the famous picture of the Earth taken from the moon: "The flow of energy through a system acts to organize that system."

Morowitz was working on molecular organization in an attempt to be more precise about the origin of that organization in natural processes. He detailed quite nicely the way in which photons of the right frequency could enter at one point in a semi-closed system (being closed to material inputs or outputs), be absorbed by simple molecular or atomic components in which electrons were thus excited and new bonding arrangements could occur. Energy that ended up in thermal modes would tend to excite molecules at the entry end of the system and cause material cycling (convection) to organize the molecules dynamically. Thus both structure and motion ensue from the influx of the right photons. He went on to analyze things like the information flow due to changes in structure and function, important to our understanding of life.

As any good disciplinarian scientist, he felt uncomfortable with too much generalization from his basic insights (personal communication). But I am not constrained by good disciplinarian constraints since I like to find generalizations that do seem to apply across disciplinary boundaries. In this case I argue that the energy flow principle is, indeed, quite general and a good explanation for the evolution of organization and complexity in all systems, not just molecular in nature.

When Morowitz says "acts to organize a system" I would amend this to "enables the organization of a system to emerge". The energy flow doesn't so much cause a specific organization to evolve as it is simply a necessary condition for any organization to emerge. In fact any given system of some nominal potential complexity might evolve in any number of ways toward higher realized complexity. The energy flow supplies the needed potential for work to be accomplished. Here, by work, I mean all manner of reconfiguration of matter as new associations and movements are enacted. Work is what energy enables, but exactly what work depends on what materials are in the neighborhood at the same time the energy is available.

For that we have to rely on something that resembles chance but in fact is itself inherently organized, and that is chaos. Ilya Prigogine, at about the same time that Morowitz was wrestling with the internal mechanics of organization evolution, had an equally useful insight into the nature of systems in which there was no apparent organization of components, but tended to evolve organization over time. He called these (what I have labelled potentially complex) systems as chaotic. On close examination one finds that such systems are not truly random. They actually do have some kind of structure, like a waterfall; the pathway of the falling water, in bulk, is readily predicted, or the boundaries of the waterfall are observable, but the fate of any given molecule of water as it approaches the fall is completely unpredictable. Turbulence in a stream is another example of chaotic systems. If you ever stare at a rushing stream you will see that eddies appear quite regularly at certain points due to the underlying rock formations. But you can't predict with any accuracy when an eddy will appear (or even exactly where within some general boundary).

Chaos in a semi-closed system imposes some kind of overarching organization, generally limiting the kinds of interactions that can happen. It is inherent in Morowitz's convective cycles; organization of flows and possible sorting (say by weight differences) of components lead to higher probabilities of certain interactions over just any arbitrary ones, a concept touched on by Dan Dennett in *Darwin's Dangerous Idea*, (1995, Simon & Schuster) which he called "forced moves".

Thus, the argument that order (or I prefer organization) can emerge from chaos (the concept led Prigogine to get a Nobel Prize in Physics!)

The key, however, remains the flow of the right kinds and amounts of energy through the system. Solar influx through the Earth's atmosphere and hydrosphere power a large majority of organizing work on the surface of the planet, with contributions from geothermal and tidal forces. And the Earth went from a hot ball with poisonous gasses swirling around it to the blue green dot that graced the back of the Last Whole Earth Catalog.

Realized complexity obtains from the on-going pumping of energy flows through the system. Over a sufficiently long time, and assuming there is a steady-state flow of those energies, components tend to organize and reorganize generating increasing complexity at a given level. Evolution is the emergence of some new subsystem, at that level, followed by active selection for or against that subsystem by the rest of the whole system. After a while, the fittest subsystems come to dominate even while chaotic variations still give rise to new variants. Occasionally a new variant is 'more' fit under the general circumstances and it survives. When these subsystems are, themselves, capable of replication, as a living system is, then the newer variety will displace the older ones.

And then, at times, with the continuing flow of energy in which there are energies not completely used for work processes (they just pass through as it were), the subsystems will have a tendency to discover yet new interactions with one another that give rise to a new level of organization. This is exactly the case when single celled organisms evolved into multi-cellular ones. New econiches are just organizational gaps where new energies are made available and a new subsystem can exploit those energies to develop new structures. In one sense we see complexity at a given level go down when this happens. Individual cells in a multi-cellular organism can begin to specialize, thus not needing to maintain all of the internal metabolic mechanisms for doing everything themselves. They can get some of what they need from nearby cells that have specialized to produce that particular product. Cells became simpler while organisms became more complex. This process gives rise to hierarchies of organization. In general, the net realized complexity of the whole goes up. More energies that formerly may have escaped untransformed by work to heat are now used for new work. Some of those previously unused energies end up captured in new structures (conformational energy) as the whole system develops greater realized complexity.

Multi-cellular organisms continued to evolve up the phylogenetic tree of life and way out on one of the newest branches of that tree sits an ape that has a spectacular brain and something we call second order consciousness. They are conscious of being conscious. They have abstract communications both spoken and written. And they start to exploit all kinds of previously inaccessible energies to supplement their normal biological food. They evolve complex social interactions because they have an increasing wealth of energy from these external sources. The potential complexity for these beasts is staggering. And they proceeded to evolve as many as they could given the chaotic constraints on their clustering.

A new level of organization appeared as societies. Culture captures the degree of complexity, but look at what happens for individuals. Just as cells in multi-cellular organisms could become 'simpler' by specializing, individual humans could simplify by specializing in the work that they performed. As they did so the total realized complexity of society increased but the life of an individual tended to become less complex. At least for a while.

This brings us full circle to Joe Tainter's point. At any given flow rate of energy available to do work, a social system reaches the maximum complexity that solves problems for the system as a whole.

In Morowitz's model, we need to ask, what happens when you reduce the flow of energy through an organized system? The reason this question is crucial is that that is exactly what is happening to our human societies. The peak of oil production represents something even more pernicious to society, the peak of net energy to do useful work in our economy (see: "Economic Dynamics and the Real Danger"). What happens to Morowitz's systems when energy flow declines? The simple answer is they go back to chaos.

Tainter documents how societies that reach the limits of marginal returns on increased complexity and then something bad happens. They collapse. What about a world in which we have 'artificially' increased the flow of energy by using fossil fuels (far above real-time solar influx) so that we can evolve much higher orders of realized complexity than can be sustained once those fossil fuels start to decline? Have we not reached our point of maximum complexity where every investment in more complexity brings less actual return in benefits? And might it not be due to the fact that we have reach some kind of maximum flow of energy?

That is the problem we face as a global civilization. We are running short on oil and as a consequence we are going to find it harder to extract other energy and mineral resources. Our net energy is already in decline and that is at the root of the global economic problems we are seeing. The simple truth is that you cannot have a growing economy when the basis of all economic wealth production is in decline. You cannot make up the difference with efficiency gains (and in reality there really aren't many actual efficiency gains to be made). The scope of energy flow due to fossil sunlight is just unbelievably huge. Neither will we make up the difference with alternative, sustainable sources (like real-time solar influx) because we can't build out the scale of infrastructure that would be required in any reasonable time frame.

We can only start simplifying our societies and giving up the many discretionary expenditures of energy that we currently enjoy without much thought. We can learn to once again live on real-time solar influx via our food raising systems. And even then we are talking about an ability to support only a small fraction of the current population. Ironically the simplification of society involves the increasing complexity of individual lives. What this means in practice is that each individual must start to become more of a generalist in terms of the functions that support life. Everyone will have to become a food grower! Believe it or not that isn't simple! Knowing how to grow your own nutrients is actually quite complicated and will demand a whole new set of cognitive skills.

I suppose it will be hard to see the similarities in the dynamics of molecules, or cells, and those of human societies for many people. It is a very abstract viewpoint. It might seem inhuman! But if there really is a correspondence, a general law of complexity evolution based on energy flow then we might be wise to pay attention.