Sustaining Human Society in a Rapidly Changing World

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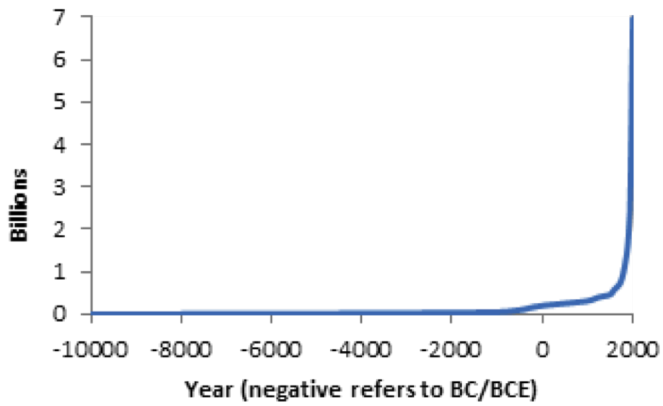
The setting

It's a truism that we live in a fast-changing world, but allow me a moment to review how massive the extent of that change can be. I'm not thinking primarily of technological developments like cell phones, personal computers, social media, GPS, and drone aircraft, for example, but rather of the underlying changes in the structure of human society that may be associated with these and other developments. The revolutions of the Arab spring of 2011 and those that are even continuing into 2013 would almost certainly not have been nearly so successful without some of these technological communication tools, but the ultimate changes that have been set in motion are in the culture, social structure, and governance systems of the affected populations. The explosive growth of online commerce has changed the competitive landscape in many industries, leading to global shifts in employment patterns and wealth distribution. Similarly, the growing dominance of computerized market trading now facilitates capital flows on millisecond timescales and the potential for unexpected and uncontrolled surges such as the market flash crash of May 2011. The combination of somewhat unpredictable tools, chance events, and imperfect human judgment can lead to spectacular financial disasters and institutional meltdowns, with implications for political leadership and national policies. The same is true in warfare, where an operator in front of a computer screen in a secure location in his or her home country can push a button to release a missile from a drone aircraft and assassinate a political or military leader thousands of miles away. What are the future implications of this kind of technology as it inevitably spreads?

But this is still just "small stuff." The world map I studied geography with in the 1950s hardly resembles the one used today. Not only do so many of the countries have different names, but they have different boundaries and different alignments. Some are parts of empires that have since disappeared. The map has literally been redrawn. If we were to go back and look at a map from an even earlier time we would find similarly stark changes, and repeating this process would lead us back in time through a progression of innumerable states, tribes, civilizations, and empires that have arisen and then declined or disappeared, sometimes gradually and sometimes in the "blink of an eye." The world is littered with the ruins of well-developed civilizations from the past, and the economies of some modern countries have largely devolved into leading troops of tourists through these ruins and admiring what wonders those earlier people had and lost.



Estimated human population size over 12000 years. (Note: there is actually no official year "0.")

But so far this all focuses on the human species more or less independently, and human history is only a tiny part of the history of life on Earth. The latter is also a story of spectacular successes and disasters. Dinosaurs came to rule the Earth, and then they collapsed into oblivion, except for the single branch that evolved into modern birds. The passenger pigeon was the most populous bird in the world just a few hundred years ago, sometimes darkening the sky with flocks of up to a billion at a time, but the last such bird died in the Cincinnati zoo in 1914. Scientists who study the evolution of life on earth point to five dramatic past extinction episodes that wiped out a huge portion of the life forms present at the time, up to 90%. They also suggest that we are right now experiencing the sixth major extinction in the history of the Earth, this one having been brought on by the growth and assault of the human species. This should not be surprising if you look at the exponential growth of the human population in a relatively short time span, as shown in the accompanying figure. Take any species you can think of — coyotes, deer, bees, mosquitoes, tigers, sharks, etc. — and just imagine what havoc would be unleashed upon the world ecosystem if they underwent a population explosion similar to that of humans. Even though these other species might be trying instinctively to spread and multiply, they just can't pull it off to the same extent because it's such a monumental task to scoop up the available resources so completely and beat out the competition from other species. But we humans have evolved a more powerful intelligence that has grossly modified evolutionary patterns and enabled us, at least temporarily, to become masters of the Earth. Where are things going from here? That's a big question!

The role of mathematics

You may be wondering how mathematics fits into our understanding of the issues mentioned above. The short answer is that mathematics is almost always involved when we are trying to understand change. If you've studied calculus, you know that the most fundamental concept studied is that of the derivative, and all the derivative is is the rate of change of one quantity respect to another, which might be time or something else. In another vein, in probability and statistics we study the occurrence of random events and we look for patterns that might enable us to understand them better because those events might bring major changes. Even more fundamental than these examples, mathematics is the basic methodology we use to measure and try to understand anything they can be expressed quantitatively, and the structure and sustainability of human society is intimately tied up with quantitative variables and issues. Examples include climate patterns, resource availability, distribution of wealth, relative strength of nations, spread of disease, management of economies, genetic evolution, and the list could go on and on. Many different kinds of mathematics are used in these investigations, and when the principal focus is on some complex system where many of these issues must be looked at in an integrated fashion, the research is often characterized as belonging to the field of "complexity theory." This is a fast-growing field and a highly interdisciplinary one. Let me highlight below some of the key mathematical methods that are often utilized in this kind of work.

Differential equations. Differential equations are used to model the relationship between variables, usually beginning with some basic assumptions about how the rate of change of one variable is related to its own value and the values of other closely connected variables at any moment in time. A classic example involves two populations of animals, one a prey animal and the other a predator whose survival depends on the size of the prey population. You can see that these two populations are closely connected, and in fact the mathematical analysis shows that the relationship between them is quite interesting. For example, when the prey population is large, the predators have lots of food and their population starts to grow quite fast. But that soon leads to an overpopulation of predators, which can wipe out at least much of the prey population; that in turn causes the predator population to drop because of lack of food, and then the whole process can repeat the cycle. The interacting dynamics of two such populations are not found only among animal species. We find similar processes at work in other fields such as economics, where similar "boom-bust" cycles occur with notable frequency and with quite harsh impacts from the down-cycle phases. A follow-on question then is what would happen if we changed tax or monetary policies to try to smooth out the system. Differential equations are an essential tool in making predictions of this type.

Probability and statistics. These closely related subjects are used routinely to analyze data and draw conclusions in many different fields. For example, we analyze clinical trials of new medicines in order to estimate whether they might have significant benefit in treating disease. Standard statistical methods are useful and highly reliable in supporting conclusions about the "average" or "expected" behavior of something. Somewhat more challenging is the problem of estimating the risk associated with relatively low probability events that might have quite disastrous consequences for the smooth running of some system, such as a nuclear power plant (e.g., Three Mile Island), a company (e.g., the hedge fund Long-Term Capital Management), or even a species (e.g., the dinosaurs). Estimating the risk from low probability future events is vital to future planning because we have to decide whether such risks are large enough for us to invest in protective actions, such as abandoning nuclear power, instituting expensive regulatory oversight programs, or designing equipment to destroy asteroids that might be headed for a collision with the Earth. Advanced methods continue to be developed to improve the reliability of such risk estimates.

Simulation. This methodology is partly a combination of the previous two, aided by extensive machine computation. To return to the case of the interacting populations, ecologists would tell us that most interactions are much more complex than just involving two species. Any perturbation in even a single population usually has repercussions up and down the food chain and through an entire ecosystem, many of them not well predicted in advance. You have probably heard of aggressive efforts to combat invasive species, both plants and animals, because of the way their impacts propagate through such ecosystems. As the number of species and variables increases, it becomes harder and harder to manage their mathematical modeling by differential equations alone. To further complicate the situation, in many cases we need to overlay an important chance or "stochastic" component on the basic principles we would like to capture in our model, and we get an extremely complex combination of interacting parts. In fact, to get the kinds of information that is sometimes needed, we may even want to model individuals in a population, rather than the population as a whole. A relatively new technique called "agent-based simulation" has achieved prominence recently because it enables us to develop a model of a system with many parts, all potentially behaving independently according to their own rules, as well as with variations due to chance. In fact, it enables us actually to “watch potential futures” play out visually on a computer screen with accompanying tables and graphs summarizing key data (e.g., the size of different interacting populations) over time. Very powerful insights can emerge from experimenting with these kinds of models.

Evolutionary game theory. Everybody knows something about games and strategy, ranging from sports to rock-paper-scissors to chess, but most people have probably not thought of evolution in the same context. But, in fact, evolution is indeed a game being played among a large number of species, and both competition and cooperation permeate the many turns and twists that arise over time. Even the predator and prey from the earlier example are actually cooperating as species because, among other things, while the predator population is being supported by the prey population, the predators tend to weed out the weaker prey, thereby also encouraging the propagation of stronger genetic lines within the prey species. Even while such a game being played at one moment in time, the whole environment in which it is being played is actually changing in time because of species changes. For example, mammals did not do very well when the dinosaurs ruled the earth, but when the dinosaurs fell victim to some catastrophic climate changes, this changed the set of players with whom the mammals were engaged, thus enabling them to develop into more dominant roles. There is a fascinating body of mathematics associated with understanding evolutionary processes, both in terms of individual genetic changes over time and in terms of the evolution of ecosystems considered as a whole. We can apply the framework of evolutionary game theory not only to natural systems, but even to the design of laws, regulations, and policies, all of which basically modify the ecosystem within which various participants interact. A good example is the design of carbon emissions taxes and credits to counteract global warming.

Network theory. Our daily lives depend on numerous networks: power, Internet, food delivery, organizations, etc. Some networks are quite robust to disruptions whereas others too often seem to crash. There is an elaborate mathematical framework for studying networks, and it has been used for everything from fighting terrorists to designing cell phone systems to planning entire economies. In fact, many of the phenomena alluded to earlier in this essay actually take place within a network structure. Sellers and bidders for stocks and commodities interact over a network. Species are part of an elaborate ecological web or network. Agent-based simulations are often conducted using a network framework connecting the agents. Thus it is easy to understand how the mathematical characterization of network structure and performance can be a valuable contributor to designing networks in a way that best preserves or contributes to the smooth or efficient functioning of society.

Suggestions for further reading

A more complete survey of the themes treated in this essay can be found in [1], which focuses on collapse and how common the dynamics of collapse processes seem to be across very many fields. There are many good textbooks on differential equations, and those that emphasize the qualitative theory are most in line with the issues discussed here. Similarly, there are of course also many good texts on probability and statistics, but the specialized subject of extreme value statistics (i.e., rare events) is best approached through books specifically on that subject, such as [2]. For agent-based simulation, a good introduction can be obtained by downloading the free NetLogo program and experimenting with the models [3]. A review of some important applications can be found in [4]. An excellent reference on evolutionary games is [5] and one focused on evolutionary dynamics is [6]. Reference [7] is an excellent survey text on networks.

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