One serious problem inherent in Houghton's assertion is that exponential economic growth is not sustainable. (The economic growth may stem from increases in population or levels of consumption; at the present time, we have one or the other in most places and both in some.) Establishing that there are limits to growth (of population, economic activity, or most any tangible entity) does not require a computer model or anything other than a sharp pencil and a conscious mind. It is easy to calculate that 2^{10} equals 1024, so 2^{20} is greater than 1 million. The US gross domestic product (GDP) increases an average of about 3.5% annually, so in 50 years it would expand by a factor of approximately 5.6. Is that plausible?

The debate over limits to growth dates back to Thomas Malthus (1766–1834), who treated the question of population, but it did not acquire much urgency until the 1960s, when computer simulations predicted an end to growth for any foreseeable scenario. Obviously, both population and economic activity are limited, but political and cultural values can allow a lot of people to live at the subsistence level or fewer to enjoy affluence. It was only later that the scientific community became aware of chaos and the fact that the modeling of nonlinear systems can be unworkable even for rather simple cases.

How can we generate a numerical estimate for the magnitude of the limits to growth? The ecological footprint, basically an accounting rather than a modeling methodology, provides an answer. The world's level of consumption is already beyond sustainability.[1]

Global warming is merely the crisis du jour. It was not even considered in the computer simulations done more than 40 years ago. That it is a serious potential problem is attested to in a rather cautious statement from the American Geophysical Union.[2] Can it be contained by spending as little as 2% of the annual growth in GDP? For the US, that would amount to about $10 billion in the first year. That may sound like a lot of money. However, some technologies, like carbon sequestration, solve the problem but are untested; others, like fission reactors, are expensive and resource intensive; and some, like fusion reactors, do not exist at all. That $10 billion might be more than enough to cover the cost of research, but it won't come close to covering the capital investment. Then one needs to add in the problem of global peak oil production, for which time-frame estimates range between 2006 and an optimistic 2030. Rising demand for fuel and the resulting higher prices have increased the use of fuel sources such as coal, tar sands, and synthetic petroleum that produce much more CO_2 for each unit of usable energy.

Another challenge to addressing global warming is the need for an unprecedented level of international cooperation, given the conflict between developing and mature economies. What one actually sees happening is a race among nations to claim the seabed that is being exposed by the melting of arctic ice. It is even conceivable that global warming could boost growth by providing access to petroleum and other mineral resources before rising sea levels curtail economic activity.

The scientific community has been derelict in its duties. Economists and politicians have been offering growth as the solution to every conceivable problem that plagues humanity. Except for a very few of us,[3–5] the physicists and other scientists who should know better have not challenged the economists or the politicians.

References

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Random thoughts on densest packing

I really liked Paul Chaikin's Reference Frame, "Random Thoughts" (PHYSICS TODAY, June 2007, page 8). However, he overlooks the problem of uniqueness. He states that face-centered cubic packing "has recently been proven to be the densest packing." However, FCC can't be the densest because hexagonal close packing is just as dense. FCC and HCP have exactly the same packing density,[1] 0.74. That something with a certain property exists doesn't automatically make it unique with respect to that property. Furthermore, both FCC and HCP have equal thermodynamic stability according to the ideal gas laws that Chaikin presents.

The lack of uniqueness has a certain relevance to the issues of random ordering. Suppose a random ordering is found that has more thermodynamic stability than a crystal. Other forms of random ordering may have the same degree of thermodynamic stability. However, can one even define a random order that is also unique?

Reference

1. C. Kittel, *Introduction to Solid State Physics*, 7th ed., Wiley, New York (1996), p. 17.

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Thank you for publishing Paul Chaikin's "Random Thoughts." Chaikin is discussing the most fundamental unresolved problems from the physics and complexity viewpoints: What is random, and what is ordered? Even more interesting is that another fundamental quantity—organization—is created at the interplay between randomness and order at the "edge between order and chaos." Organization, though fundamental for all complexity considerations, can be defined only after we know quantitatively what exactly randomness and order are. That fact makes their definition even more crucial and urgent.

After we have defined organization, we will be able to find out how to improve it and what a "higher level of organization" means. Those discoveries have implications beyond physics and will help us to deal with the constantly changing organization of our complex society.

I even want to speculate that if we understand what organization is, we will be able to improve it and thereby make our lives better. After that, we can start pursuing answers to even more fundamental questions: Is our three-dimensional world best suited for organization? How much organization will be allowed in more or fewer dimensions? A world in how many dimensions allows the best organization? Do we live in the best of all possible worlds? Do multidimensional worlds with higher levels of organization than ours already exist, and are they far ahead of us?

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In an otherwise illuminating Reference Frame, Paul Chaikin presents the conundrum that an ordered state has a higher entropy than a disordered state. That in turn raises a question regarding the physics of gravity being omitted from analysis of the problem of whether higher entropy and higher disorder go together.

Chaikin describes the ordered face-centered cubic (FCC) state of packed spheres as being stable because of its "higher *entropy* than the disordered state, as unintuitive as that may be." The "ill-defined" disordered state of random packing is experimentally achieved by "tapping" the container in which the spheres reside until the density maximizes, which occurs at lower density and looser packing than the FCC configuration.

However, except in orbit, that procedure is necessarily carried out in a gravitational field, so that the total (potential) energy is minimized, rather than the entropy being maximized, when the system is allowed to come to rest. (The kinetic energy is dissipated and therefore irrelevant.) Yet that gravitational contribution to the physics does not appear to have been included in the analysis. Despite the dissipation, the system will not compact without the presence of the gravitational potential gradient, or some other applied, one-dimensional force, such as that due to entrainment in a fluid flow. How might this problem change if the force were 2D, radiating spherically inward, for example?

Moreover, the FCC packing condition is achieved in one and two dimensions, but not three. That fact invites consideration of the result if a fourth dimension were available during the tapping process, although the final configuration is still restricted to three dimensions.

Of course, such a test can only be carried out by a nontrivial computer simulation. However, just as motion transverse to the plane opens wide the path to the equivalent of the FCC configuration in two dimensions, it seems intuitive that the vast additional phase space available with a fourth dimension can unblock the path for three dimensions. But that would still seem to minimize potential energy rather than maximize entropy.

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Chaikin replies: The readers' comments remind me of occasions when I've run over the time limit while giving a talk, and the first question is, "What would you say if you had another 10 minutes?"

In response to David Rosen, I offer the following. Several infinite structures have the same 0.74 packing fraction as the face-centered cubic structure. In referring to FCC, I was following the spirit of Thomas Hales in his 2005 paper on the proof of the densest packing in three dimensions.[1] According to his theorem 1.1, the Kepler conjecture, no packing of congruent balls in Euclidean three space has density greater than that of the FCC packing.

Equivalently high packings are found by stacking planes of hexagonal close-packed spheres. Each sheet of spheres is placed so that it sits in the interstices of the previous hexagonal sheet. There are two sets of interstitial sites: B and C; the first layer is called A. The following are some common stackings: ABCABCABC, the FCC structure; ABABABABAB, hexagonal close packed or HCP; and ABACABAC, double HCP, a structure found for some lanthanide and actinide elements. And ABCBACBCBACABCA is random HCP, the structure found in many colloidal crystals. However, the number of such configurations grows exponentially with the length of a sample rather than its volume and thus does not contribute to the sample's entropy.

I also found Terry Goldman's comments interesting. Strangely enough, several research groups, including my own, have performed crystallization experiments on colloids in microgravity during orbit. The physics of the liquid-to-crystal transition is the same in space as on the ground. That is because the transition has its basis in the purely geometric problem of particle packing. Using the crystal and random packing limits that researchers have found in experiments on granular systems, we can evaluate the entropy of a system at lower densities, and the ordered state has the higher entropy. For molecules on Earth and for colloids in space, thermal energy dominates gravitational potential energy, and entropic effects produce the crystallization with which we are familiar.

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A brief etymology of cybernetics

In Robert Park's stimulating review of Steven Jones's *Against Technology* (PHYSICS TODAY, April 2007, page 59), there is an historical error: Although Norbert Wiener did use the term "cybernetics" in his 1950 book, *The Human Use of Human Beings: Cybernetics and Society* (Houghton Mifflin), he had already brought out a book in 1948 entitled *Cybernetics*.[1] I still have a copy that I bought in December 1948 when I was studying mathematical biology at the University of Chicago.

Apparently, André Ampère had already used the term *cybernétique* to describe the art of government, and much earlier Plato used the Greek term *kybernetes*, meaning governor and steersman, in conjunction with governance.

Of interest in conjunction with Jones's book and Park's review is the wide-ranging introduction to Wiener's book on cybernetics, which he wrote in 1947 while he was at the National Institute of Cardiology in Mexico City. Wiener expressed concern that those who have contributed to the then-new science of cybernetics "stand in a moral position which is, to say the very least, not very comfortable," because they are contributing to the concentration of power, which always tends to end up "in the hands of the most unscrupulous." He offered, nevertheless, the "very slight hope" that a better understanding of man and society would result.

Reference

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Science on stage: Minor clarification

In my reply to William Bennett (PHYSICS TODAY, February 2008, page 11), one awkward phrase has left an impression I did not intend. *American Theatre* magazine did not request that I write a rebuttal in response to Kirsten Shepherd-Barr's book *Science on Stage: From "Doctor Faustus" to "Copenhagen."* The magazine editor requested a review, which turned into a major rebuttal as it developed.

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Spontaneous knots and the law of snaggature

What a pleasure to read the brief story on how string spontaneously forms knots (PHYSICS TODAY, November 2007, page 19). The report immediately called to mind my late father, Paul S. Cohen, from the College of New Jersey's chemistry department. He formulated—only half in jest—what he termed the "law of snaggature," which states that everything in the universe spontaneously snags everything else, including electrical cords, ropes, string, cables, threads, hoses, and any other long, narrow, flexible objects. While he was confined to his hospital bed during his last days three years ago, he even joked about snaggature concerning his IV tubes.

How I wish I could show him this article. I know he would be immensely pleased to find out he was right.

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