On the Confounding of Overshoot and Collapse Predictions by Economic Dynamics

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Abstract

At the 19th International Conference of the System Dynamics Society held in Atlanta, Willard Fey and Ann Lam (2001) asked why system dynamicists by and large believe that the world population is limited and yet don't act on this belief on a day to day basis.

Because this is a deceptively difficult question, this study addresses it from several different perspectives. From the literature, it examines current critiques of *The Limits to Growth*, Malthus, and Simon's bounded rationality. The study finds that theories, predictions, and criticisms concerning complex systems cannot be answered definitively. Instead both the initial theory and its criticisms must be considered together, a conclusion supported by 20th century philosophy.

From this perspective, instead of offering definitive, closed-form solutions, three heuristics are developed. The first contrasts notions of possibility and prediction from an information theory perspective. The second examines the mechanics of standard overshoot and collapse systems and how collapse predictions can go awry. Third, an example of overshoot and collapse is examined with an eye towards timing the collapse and understanding how decision makers interpret information from within the system. Systematic errors from this smaller, economic system are then applied to Fey and Lam's concern regarding world population, a system that may have overshot but has not yet collapsed.

1. Introduction

At the 19th International Conference of the System Dynamics Society held in Atlanta, Willard Fey and Ann Lam (2001) discussed, explored, and furthered some of the key themes of *The Limits to Growth* (Meadows et al 1972). Although many of the discussion's details have faded over time, one portion of their question and answer period remains vivid. It was asked of the plenary session audience how many believed that the Earth was in the midst of an overshoot and collapse scenario. Almost all raised their hands. Then it was asked how many people were actively accounting for this possibility in their day-to-day behavior. Almost every hand went down. This raises a question: Why is it that an entire room full of system dynamicists believed that something quite catastrophic was likely to occur and yet few were doing anything about it?

This paper seeks to construct a plausible answer for this question while understanding that the source of this question is likely to be subtle, systemic, and hidden. First, it is recognized that this is a levels of analysis questions, which – within the international political economy literature – reveals itself in several different forms and contexts. Harold and Margaret Sprout (1965; 1968; 1971) posit an ecological triad of entity, environment, and entity-environment interaction: entity and environment constitute two separate levels of analysis, with their interaction forming a dynamic, third subject of study. Waltz (1959) forwards a multi-level structure consisting of three images – man, the state, and the international system. North (1990) extends this structure with a fourth image, the *world system*, that captures and allows for global environmental degradation. Hardin (1968) addresses the problem by exploring the microeconomic decisions that lead self-interested, rational people to collectively and unintentionally degrade their surrounding environment. Meadows et al (1972) examine the long-term consequences of these micro dynamics from a macro, planetary perspective.

This paper begins by reviewing current critiques of *Limits* with an eye towards understanding the basic argument as well as its underlying assumptions regarding reason, evidence, and inference. In so doing, a number of underlying philosophical debates are rediscovered, and these are quickly reviewed in Appendix A. After establishing the terms of the debate, answers are forwarded in the paper's second section. In the grand systems tradition, a single definitive answer is not offered; rather, three dynamic responses are reviewed that together would confuse a boundedly rational decision maker living within a complex surrounding and supporting environment. These dynamics, including economic dynamics, complicate and confound predictions based on overshoot and collapse dynamics.

2. Establishing Questions

This section addresses three variations on the *Limits* theme. The first directly addresses *Limits* and the work on which it is based, Forrester (1973), by examining two recent criticisms. The second looks to interpretations of an earlier and related work by Thomas Robert Malthus (1798). Finally, because the driving question and their ultimate answers derive from a tension between macro-level economic dynamics and micro-level decision making, a work relatively unrelated to *Limits* is examined regarding macroeconomics and rationality by Herbert Simon (1983).

2.1 Forrester

The 20th Century saw an unprecedented increase in the world's human population, which has led to a literature regarding the threat this might pose -- Forrester (1973), Meadows et al (1972), Meadows, Meadows, and Randers (1992), Fey and Lam (2001), etc. – that predicts the global environment will ultimately prove unable to support this still growing human population, leading to a worldwide environmental and population collapse. Recent critics including *The Economist* (1997) and Lomborg and Rubin (2002) have pointed out that early predictions made by these researchers have been proven incorrect.

The Economist (1997) focuses its criticism on predictions made by Meadows et al (1972) regarding predicted shortages of oil, natural gas, silver, tin, uranium, aluminum, copper, lead, and zinc. They also address Meadows, Meadows, and Randers (1992) who predicted food shortages as well. In each case, the envisioned shortages did not occur because of the economic dynamics of exploration, innovation, and substitution. If a shortage was about to occur, as indicated through market pricing, new supplies or substitutes were found through the natural workings of the market. Such faulty predictions are grounded in misspecificifying the overshoot and collapse archetypical dynamic (see section 4.2), and thus mispredicting the limit of human population growth. This error was made by incorrectly counting the underlying resource base on which the world system is based and thus mistiming when it would become exhausted. Economic dynamics, the normal workings of the international market, enabled and extended the global growth dynamic well beyond that initially envisioned by *Limits*. From this experience it can be inferred that when the underlying resource base is a complex system, 1) it is hard to count the stocks in the system, 2) it is hard to understand the relationships among them, and 3) it is hard to understand how the market will find substitutes for depleted stocks. Thus the world economic system may be headed toward collapse, but it hard to predict exactly when and how this might occur.

Lomborg and Rubin (2002) move beyond simply noting failed predictions to offer explanations about why this might be so. These explanations tend do be economically but not dynamically informed, so it makes sense to review them in order to understand not only how they might be improved but also how the original systems-based predictions might have been improved. Lomborg and Rubin (2002, 42) contend that, "Due to an exponential increase in population growth, the world should be facing desperate shortages of arable land and rising food prices," but this assertion denotes a misunderstanding of the overshoot and collapse dynamic. It is perfectly reasonable for an unsustainable, exponential growth dynamic not to exhibit shortages, at least initially. The question is one of relative timing (see section 4.2 for details). Growth processes can continue until they are limited by shortages of underlying resource, in this case of land and food, with the limit likely arriving rapidly and unexpectedly.

Lomborg and Rubin (2002, 43) continue, “Tempting though it may be to attribute these faulty predictions to flawed methodology and bad math, their real weakness is the underlying assumption that planet Earth has finite, essential resources (such as oil, water, and grain) for which there are no substitutes.” This statement is partially true. The world indeed has finite resources, but predicting which they are and when these limits might be reached is a difficult and inherently uncertain undertaking. As has been noted, the material expansion and temporal extension of food, minerals, and oil beyond limits previously thought possible has been accomplished through a combination of technical and market forces. But other necessities like clean air, fresh water, and arable land are not as readily expanded or substituted. Lomborg and Rubin (2002, 43) conclude, “In short there is no law dictating an exponential mounting pressure on Earth’s ecological resources. The limit of sustainability is not a static ceiling but is formed and expanded by human innovation and technological progress.” Once again, this statement is partially true. Indeed, economic dynamics have expanded the growth limits to make feasible levels of population that previously would have been thought impossible based on lower levels of innovation, technology, and globalization. But while limits can be extended, they cannot be extended indefinitely. Moreover, in systems that previously have exhibited overshoot and collapse dynamics, their limiting factors were often reached quite suddenly, dramatically, and unexpectedly.

2.2 Malthus

The predictions offered by *Limits* and their subsequent refutations are not unique. Thomas Robert Malthus, concerned about the adequacy of British farmland to support its burgeoning population, wrote *Essay on the Principle of Population* in 1798. His fears also were not confirmed, but Kates, Turner, and Clark (1990, 14) note that despite this, "almost each generation seems to rediscover Malthus." Each generation however slightly varies the chief measure of concern and the feared limiting factor. Concerns change from population growth to pollution absorption, from farmland depletion to oil and metal shortages, and from regional perspectives to the global, but the essential formulation of the question remains essentially constant – fear of dramatic environmental change.

The back and forth nature of limitation predictions and their criticisms over time thus takes the form a conversation, and from this conversation three observatoins can be made (Kates et al 1990, 14--15). First, it must be acknowledged that limit predictions and their answering criticisms cannot be "proven" true or false through logical argument or empirical evidence, at least not in any simplistic, conventional sense. Rather, like any conversation it changes as old factors and concerns drop off, new insights and questions become incorporated, and the scale and scope of the discussion changes. This leads to a second observation, that not only will old concerns fade away as new ones appear, but as time passes and generations progress, previously vital concerns will seem quaint or mystifying. It is entirely possible that the focus of study for today's models will meet that fate. This leads to a third observation, that should a prediction be proven false, the reason might not be grounded in faulty logic or math, but because the analysis was taken seriously and policies were undertaken to prevent the problem.

2.3 Simon

Herbert Simon won the 1978 Nobel Prize in economics and created the theory of bounded rationality, which exists almost implicitly within the discipline of system dynamics (Morecroft 1983). However, this study makes a slightly different observation regarding Simon's bounded rationality – that it helps to explain persistent, spirited, and almost irresolvable debates.

Friedrich Hayek, who won the 1974 Nobel Prize in economics, wrote *The Road to Serfdom* (Hayek 1944) that critiqued the then fashionable trend towards socialist, centrally directed economies. Hayek argued that such economies would fail due to information processing limitations. Economies distribute decisions across a range of owners, experts and interested others who respond to specialized technical and general pricing information. To expect that a centralized bureaucracy would be able to synthesize such information and determine accurate prices and planning policies would be essentially impossible. Moreover, prices and policies would inevitably be made to serve essentially political goals, which would cause further economic inefficiency.

From a 21st century perspective, Hayek (1944) makes good theoretical sense and has been shown historically correct. The point made here though is one of intellectual debate, and thus it is instructive to review Finer (1945), *The Road to Reaction*. The tone is, by any measure, harsh and angry. Let us resist the temptation to review the specifics of Finer (1945) and instead state consider the general tone. First, Hayek argued against trend of the age, which is always bound to provoke a reaction. Second, Hayek's argument was mathematically subtle, resting on a then ill-understood cybernetic theory and information flow to reconcile supply and demand. Third, Hayek's thesis countered something that Finer very much wanted to be true and in which he had much professionally invested. A quick google search will turn up sentiments similar to Finer's that persist even in the present day.

Quite apart from the reaction it provoked, Hayek has benefited from analytic advances, many of which were employed by Simon in his bounded rationality work. Working from the synthetic perspective of social science, computer science, and experimental psychology, Simon (1983) addresses the levels of analysis question from a Hayekian perspective. So while Simon studied a boundedly rational decision maker in a larger economy, Forrester and Malthus study individual resource consumers in a larger environment. Simon (1983) confirms Hayek from his studies of decision making within larger organizations, finding that they human mind is unable to capture the complexity necessary to make accurate predictions and process the information necessary to set accurate prices. It follows that the human mind is similarly unable to process the information necessary to represent interactions between the social economy and the global ecology, which is why Forrester (1971) advocates the cognitively prosthetic use of computers to further the information processing capability of the human mind. However, it is true that computers are similarly, though differently limited in their ability to represent reality – a fact readily admitted by modelers when they say that all models are wrong, it's just that some are more useful than others.

This section has sought to put current criticisms directed at Forrester, Meadows et al, and Malthus into perspective. Yes it is true that predictions were made that have not proven completely accurate, but is also true that there are some important, beneficial, and even true aspects of these models that should be recognized, saved, and studied. Like Finer (1945), criticisms of this work must be examined for their underlying motivation, all the while recognizing that taking such criticisms seriously does not imply accepting them completely.[1]

3. Forwarding Answers

In forwarding answers regarding current debates regarding *Limits*, one is tempted to offer "answers" because, for interesting, complex or hard problems, definitive replies of 'true' or 'false' are impossible. Instead three *heuristics* are offered that help reconcile the disparity between the initial predictions of Meadows et al. and the criticisms they evoked.

3.1 Possibility and Prediction

It is generally recognized that complex chaotic systems capture important aspects of everyday, real-world systems. Here they are reviewed to gain insights into the nature and possibility of prediction.

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[1] Finding that there is merit to both sides of the current *Limits to Growth* debate – i.e., the original argument as well as the current criticisms -- is more than just an abdication of judgment through equivocation. Instead it is a rediscovery of many of the most interesting and hard to interpret aspects of 20th century philosophy, a condensed discussion about which can be found in Appendix A.

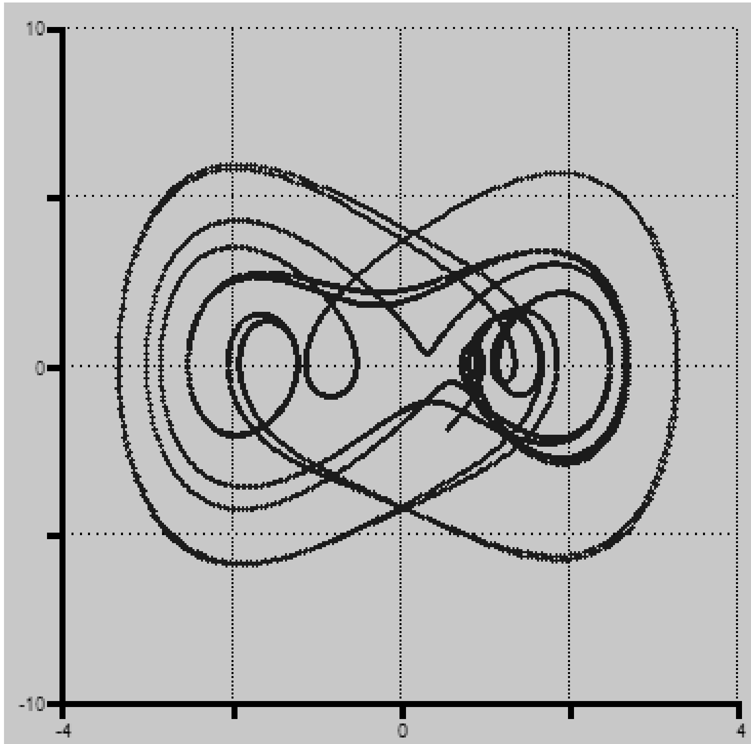

Figure 1. Duffing (Chaotic) Oscillator (Thompson & Stewart 1986, 3--5)

Figure 1 contains a representative chaotic system, a Duffing Oscillator (see Appendix B for definition), which demonstrates standard non-repeating behavior within a limited mathematical space. That is, the dynamic response never extends beyond 4 or -4 on the horizontal axis or 7 and -7 on the vertical axis, but within these limits the system's dynamic response never repeats. This observation however implies certain things about the predictability of the system. As the response moves further toward the dynamic edge or boundary, it becomes increasingly "predictable" that the response will "regress" or change direction back towards the origin.

In making this observation, we rediscover a classic result. Claude Shannon introduced the statistical thermodynamics concept *entropy* to the study of systems. The equation $S = k \log w$, where S is entropy and w is the number of possible states

(Campbell 1982, 46), is used to measure the *order* in a system, a concept that implies *predictability*. The fewer the possible states, the lower the entropy, and the more likely it is that the system will be in one of the states. Thinking about successful, long-term social predictions, there are times in history when certain events "have to happen" and other times when the future is "up for grabs." These translate to periods of high and low entropy respectively, which can be demonstrated experimentally.

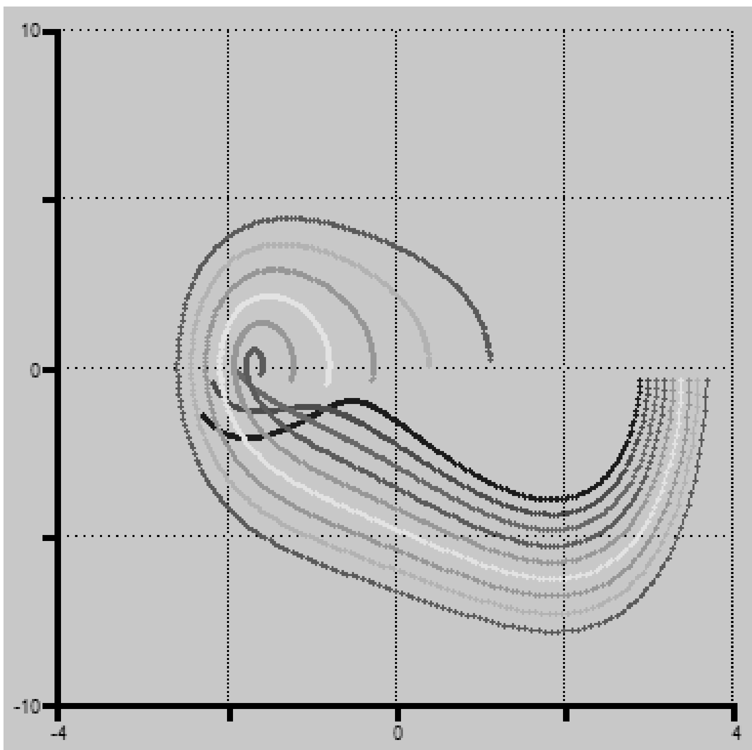

Figure 2. Point of Possibility (High Entropy)

In Figure 2, we start the simulation at nine different points at the far right side of the graph as the response heads down and back towards the left. As can be seen, at the end of the simulation the nine different curves are in nine very different places. This demonstrates two things: 1) standard chaos dependence on initial conditions and 2) high systemic entropy. Small differences at the beginning of the simulation soon become big differences at the end. High levels of systemic entropy make the simulation inherently unpredictable, and the large changes at the end -- changes that are driven by small changes in initial conditions -- make this starting point a “point of possibility” in the sense that anything can happen and the future is “up for grabs.”

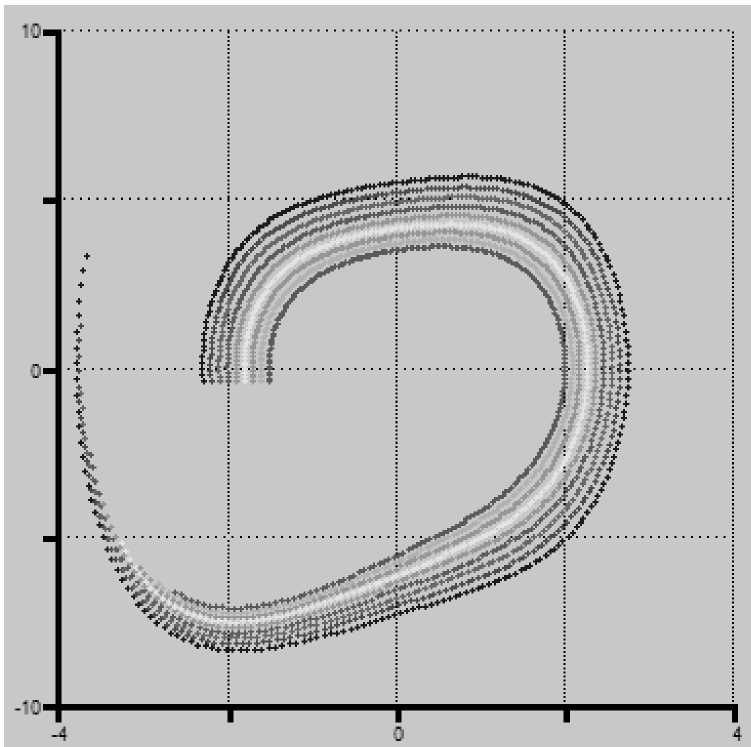

Figure 3. Point of Prediction (Low Entropy)

Figure 2 should be contrasted with Figure 3, which in some sense demonstrates the opposite side of the entropy continuum. The Figure 3 trajectories begin in the center of the graph as the trajectory pushes up and out towards the left edge. Despite different starting points, all curves end up in essentially the same place, making this part of the curve one of low systemic entropy. This is called a “point of prediction” because small differences that lead to big differences on other parts of the curves at other times make no difference here – the same dynamic response occurs regardless. Note also that although the curves all follow the same path, they do so at different times. That is, the curve on the inside of the response makes it only partway around the curve, while the curve on the outside travels much farther over the same time. Differences in relative system timing that result from different initial conditions are explored further in the next section.

3.2 Overshoot and Collapse

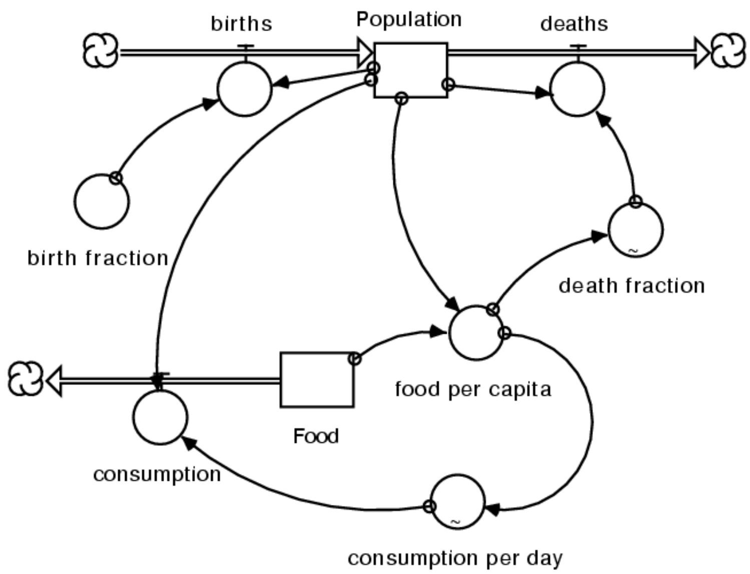

Figure 4. Overshoot and Collapse System Structure (HPS 1990, Ch. 9)

Figure 4 depicts a different type of system, one that exhibits classic "overshoot and collapse" response, as shown below in Figure 5 (for equations and descriptions, see Lofdahl 2002, App. E).

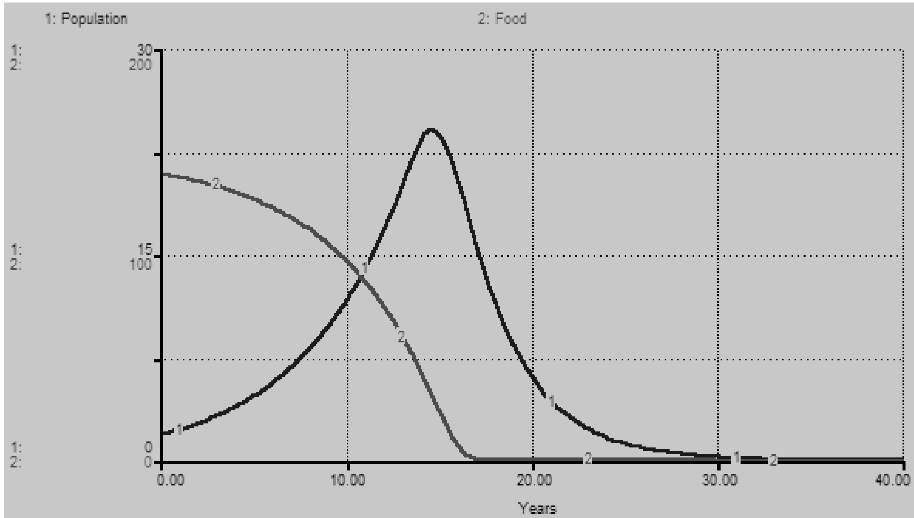

Figure 5. Overshoot and Collapse dynamic response

In Figure 5, we see just how the two Figure 4 stocks, Population and Resources, are connected: Population grows until Resources run out, and then Population "collapses" by dropping back to zero. This is the basic nature of the overshoot and collapse response.

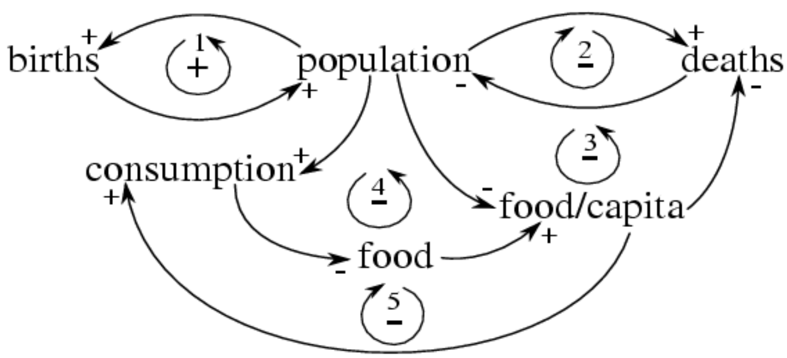

Figure 6. Overshoot and Collapse feedbacks (Lofdahl 2002, 133).

The feedback relations of Figure 6 show how the overshoot and collapse response occurs. The initial growth of Population is driven by the first, positive feedback loop. Population grows until it is limited by lack of food, at which point dynamic dominance shifts to the negative feedbacks, loops 2 through 5.

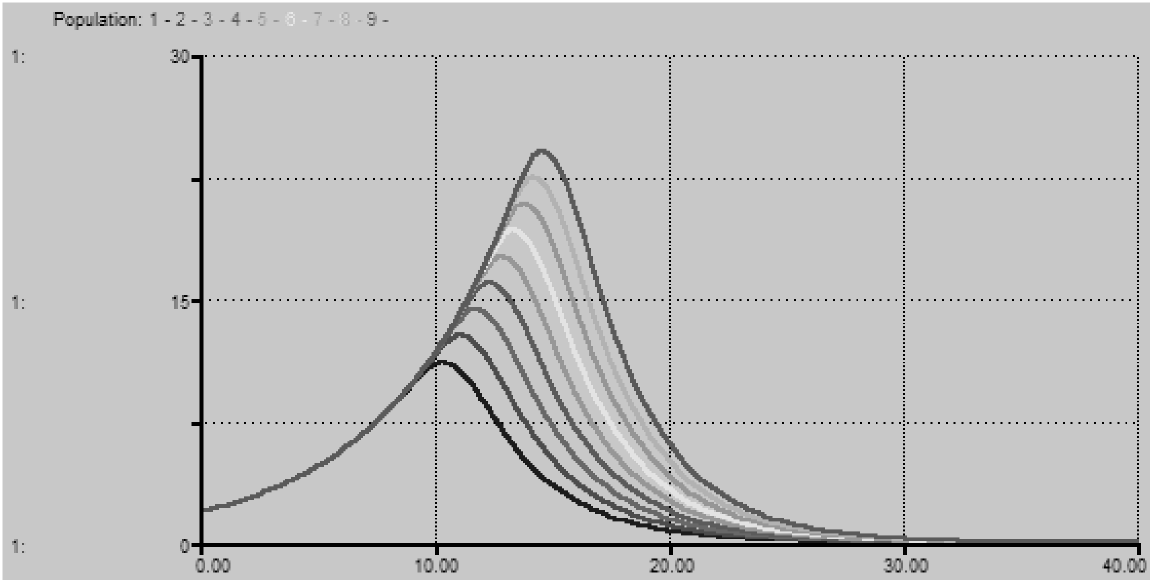

Figure 7. Overshoot and Collapse dynamic response with varying Food levels

The simulation is run with increasing levels of food in Figure 7, and two things happen: first, Population grows ever higher, and second, the collapse gets postponed ever later. Regardless of the initial food level, population collapse inevitably occurs in each run. Thus, the overshoot and collapse system is a predictable, low entropy system. Whatever the initial food value, the same result occurs, population collapse. However, this simulated system is very much an artificial one because no provision is made to grow and restore the food supply. Looking to Figure 4, food can only be withdrawn from the stock -- it cannot be replenished. Thus it can be argued that the collapse is “dialed in” and does not accurately represent the real world. This objection is addressed in the next section, in which several real-world systems are reviewed.

3.3 Economic Dynamics

Economics dynamics are examined here to the extent that they confuse and conflate the predictability of standard overshoot and collapse dynamics, which is accomplished from two perspectives. First, the overshoot and collapse system is considered from a purely macro perspective – the system as just a system. Second, the discussion expands the perspective of the sentient, boundedly rational observer embedded within the system, which entails identifying the limited information available to decision makers as well as the decisions that are likely to be made with that information.

3.3.1 Substitution and Technology Effects

Overshoot and collapse is not a topic of limited academic interest. There is a rich history of this widespread economic phenomena that has impacted many lives and had lasting effects: examples include 1) the 1593 Tulip-bulb craze in Holland , 2) the 1720 South Sea bubble in Britain, 3) the 1926 Florida real estate craze in the US, and 4) the 1929 US stock market centered on Wall Street (Malkiel 1999, Ch. 2). This study instead focuses on a more recent example, the late 1990s overshoot and collapse of the NASDAQ index, as shown in Figure 8 below.

Figure 8. NASDAQ Overshoot and Collapse (www.bigcharts.com)

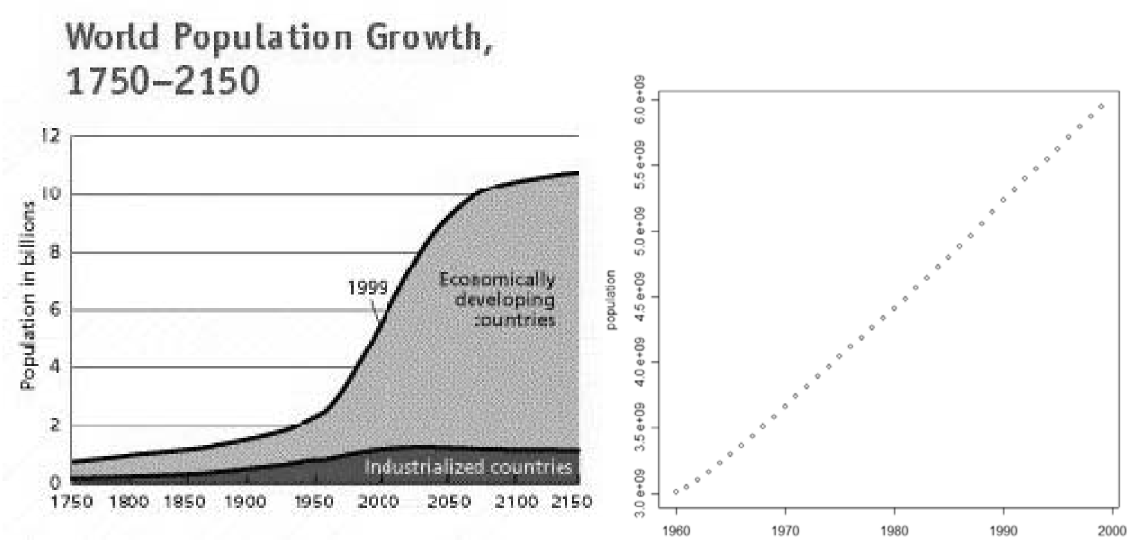

Figure 9a & b. World Population, long and short-term
(www.worldpopulation.org; World Bank 2001)

Comparing Figure 7 with Figure 8, it can be seen that the NASDAQ index demonstrates a classic overshoot and collapse response. This inquiry into the NASDAQ example is motivated by a desire to gain insights into the possible overshoot and collapse of the global environment. This includes not just the underlying systemic forces behind the phenomena but also the ways people think about overshoot and collapse and the kind of conclusions they draw at different points in the process. The NASDAQ example is chosen because much has been written on its buildup between 1996 and 2000 and its collapse from 2000 to 2002. This provides an easily accessible record of the mental errors people made with regard to the NASDAQ economic system.

Beginning with the mechanics, let us look to what caused the bubble in the first place and what eventually limited it. The story begins with the August 1995 Netscape initial public offering (IPO) that demonstrated an unexpected demand for tech stocks. Tech entrepreneurs, venture capitalists (VCs), and investment banks combined to provide dot.com companies and shares to meet that demand (Smith 2002). The problem was that the public markets valued dot.com shares at a premium but the companies themselves did not make money. The dot.com bubble was based almost solely on investment capital from the VCs and public markets. With investment capital being spent to cover operating costs, the companies had only a short time to live unless sales could be generated. This led to two questions: 1) When would sales increase to justify the share prices and allow the companies to live? and 2) When would share prices drop to the levels warranted by lackluster dot.com sales, and when would the companies die? Given the high prices tech stocks reached, the first question was eventually rendered unanswerable – share prices had to come down at some point. This left only the second question: When would the dot.com bubble end?

As early as 1996, experienced investors were predicting an unhappy end to the dot.com run-up. Barton Biggs and Byron Wien, both of Morgan Stanley, advised their investors to lighten up on U.S. stocks because they felt the system and the companies that comprised it were unsustainable (Cassidy 2002, 118—9). Unfortunately for Biggs and Wein, they were bears at the beginning of a four-year bull market that ended only in April 2000. While their analysis was sound – indeed, the business fundamentals like sales, markets, and profits were not there for long-term, successful businesses – the timing proved much harder get right due to the economic dynamics at play. The ability to predict when a system will "collapse" is only possible if it is understood when the underlying, foundational resources will exhaust themselves. In the case of the simple system depicted in Figures 4 and 5, Population decreases at precisely the time when Resources completely run out. Calculating the exhaustion point for the complex investor behavior and attendant economic dynamics that supported the late 1990s NASDAQ could have been done as an educated guess, but it would have been just a guess. The best that can be said, as depicted in Figure 3, is that entropy decreases as the system moves towards its natural limit. The system becomes more likely to collapse, but it is impossible to say exactly when. Thus the actual situation is more like that depicted in Figure 7 with varying Food levels: the larger the resource base, the larger the overshoot and the more postponed the collapse. However, since the underlying resource is a complex economic system rather than a simple homogeneous stock, its exhaustion point is harder to predict. Biggs understood this dynamic when he wrote in 1996, “I believe that U.S. stocks are overheated, overvalued and vulnerable to a bear market… The longer the craziness in the United States goes on, the higher the price we will have to pay.” (Cassidy 2002, 119) Who then would or could have predicted it bull market would continue for four years?

3.3.2 Market-driven cognitive effects

Biggs maintained his views far longer than most bears, especially considering that bulls like Mary Meeker, Henry Blodgett, and Jack Grubman were so lavishly rewarded for their ultimately unfounded optimism. In the summer of 1999, Biggs debated James Glassman, coauthor of *Dow 36,000*, in Sun Valley:

> During the debate with Biggs, [Glassman] argued that the Internet was the transcending invention of the twentieth century, more important than the jet aircraft, the contraceptive pill, and nuclear fission. Biggs considered Glassman’s argument to be ridiculous. Even the humble air conditioner had altered history more than the Internet, he said. Without air conditioning, Atlanta would be a small town and modern Singapore wouldn’t exist. After the speeches were over the issue was decided by a

> show of hands. Glassman won by 180 votes to 2. One of the people who voted for Biggs was his wife. (Cassidy 2002, 251)

The notable thing is not only is it hard to withstand the social pressure of being in the minority, but the financial pressure for fund managers is even more intense. Imagine predicting collapse in 1996, and then waiting while your clients watch their peers make money by listening to your more optimistic competition, year after year. It is still difficult to fathom both the duration and magnitude of investment funds that were made available by venture capitalists and public markets to fund the dot.com bubble, one consequence of which were the lopsided and ultimately incorrect popular views like those demonstrated in Sun Valley. Biggs was right in the long-term, but the majority, responding rationally to short-term economic incentives, reached the opposite, short-term conclusion and were ultimately proven wrong.

4. Conclusion

This paper began with a question: Why do so many system dynamicists believe that the global environment is engaged in an overshoot and collapse scenario and yet do so little about it? (Fey and Lam 2001) This paper began by reviewing three different economic thinkers – Forrester, Malthus, and Simon – as well as their critics. Then it reviewed two system dynamics models. First, a chaotic oscillator was examined noting that its dynamic response moves through "periods of possibility" and "periods of prediction." Prediction is most likely when the response moves toward the edge or limit of its range – that is, an area where no previous response has been noted. Second, an overshoot and collapse model demonstrated the relationship between growth and underlying resource responses. It was noted that the greater the level of underlying resources, the greater the level of growth that is achievable before systemic collapse. Therefore, if the quantity of the underlying resource is unknown, then so too is the amount of growth it will support.

Next a real-word example of the overshoot and collapse dynamic – the NASDAQ index or dot.com bubble – was reviewed. In this example, growth of the NASDAQ was made possible so long as capital could be obtained from venture capitalists and the public markets to fund tech companies because their low profits made them unsustainable. This was noted by stock analysts as early as 1996, but the NASDAQ did not collapse until April 2000, four years later. Two lessons can be drawn. First, growth can continue for far longer than seems possible to somebody who recognizes the systems' eventual unsustainability and foresees limitation and collapse. Economic dynamics work to expand and extend the underlying resource in ways that prolong growth and confound prediction. The strongest statement that can be made is that as growth continues, the likelihood of system limitation and collapse increases. For the individual, the growth dynamic can prove so overwhelming that the possibility of collapse begins to seem unlikely and remote as naysayers are continually proven wrong. As was the case with the NASDAQ, the actual likelihood of collapse grows ever larger, while for those under its thrall, the possibility of collapse grows ever more distant. When the system eventually collapses, it does so suddenly, dramatically, and unexpectedly.

Systems lessons from the dot.com bubble can be considered with respect to the critics of *The Limits to Growth*. Early predictions of population limitation due to shortages of oil, metals, and food have not come true. In retrospect, economic dynamics grounded in technical innovation have greatly expanded these resource bases and created substitutes when technical innovation proved impossible. This in turn has allowed the human population to reach historically unprecedented levels. Note however that there are natural resources for which substitutes do not exist including clean air, fresh water, and arable land. Moreover, the global ecology on which the world population is based is far more complex and unpredictable than the economic system that supported the dot.com bubble. Given that the strongest statement that can be made regarding a complex resource base in an overshoot scenario is that it is increasingly likely that it will collapse, it is probably premature to state that technology and innovation will obviate any natural limits to world population.

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Appendix A. Underlying Philosophical Debates

In finding that both sides of the *Limits to Growth* debate are partially correct, potential criticism that this is a simplistic equivocation in the face of a contentious and difficult question is defended against in three ways. First, the weaknesses of *logic* to describe completely the realm of mathematics and by implication reality and the natural world are reviewed. This means that, for complicated questions, sharp distinctions of 'true' and 'false' become grayer, less focused, and nuanced. Second, the notion of *falsifiability* in science is reviewed. Third, the concept of *rationality* is contrasted with more empirically verifiable notions of cognition.

A.1 Logic

The weaknesses of strong logic establish the working context for 20th century philosophy. In many ways, philosophy from the last century is unsatisfying because its most significant advances are not readily understandable, even by those who made them. First, consider the philosophical triple of Russell, Gödel, and Turing. Whitehead and Russell (1927) tried to provide a complete, axiomatic, and positivistic descriptive framework in *Principia Mathematica*. Gödel's incompleteness theorem of 1930 demonstrated that one can say something complete or provable only about uncomplicated systems, which is to say uninteresting problems (Hofstadter 1979). Complex and interesting problems can, in contrast, only be described incompletely. Interpretations of this result vary, but if one recalls that language reduces to logic, Gödel says that a logical or linguistic description of a hard and complex problem will always fail to capture the total nature of the problem or system.

Turing extends the notion of uncertainty with his theory of computation, which corresponds roughly to a deterministic or "digital" universe (cf. Wolfram 2002). While it is still a source of lively debate just how Turing applies to the real world -- some say "not at all" while others say "quite a bit" -- this theory does bear on the argument at hand. First, a Turing machine is wholly deterministic, unlike a neuron or a human mind (i.e., many neurons) that is comparatively probabilistic. Second, the whole notion of parallelism (which is present for neurons) disappears for a Turing machine because a parallel Turing machine reduces to a single, really fast Turing machine. The interesting part is this: Given a strongly deterministic Turing machine and a digitally defined input tape, it cannot be determined before hand whether or not the Turing machine will halt. Whether it halts or not must be determined empirically, by actually running the machine. And if it cannot be determined whether or not the machine will halt, neither can it be determined if it will assume any other state of interest.

So how does this pertain to determinism, probabilism, and prediction? If one cannot predict the behavior of a wholly deterministic machine with complete information, then how can one hope to predict the behavior of the semi-deterministic complex interaction between social and environmental systems with incomplete information? The answer is that the prediction of complex and interesting systems is impossible, and so the best that policy makers can do is employ heuristics that make some logical sense and have an empirically supported history of utility. (Chaos theory provides another, more physically based path to the same result. See section 3.1)

A.2 Falsifiability

Philosophers and social scientists effectively responded to this logic debate with, "So what?" That is, they initially argued that computational theory has no bearing on human philosophy. This is hard to defend because Turing's results derive from basic logic, and so it is tough to see how philosophers can employ some logical tools (i.e., the easy ones) and toss aside others (i.e., the hard ones). The more likely answer is that such results are simply beyond the analytic capability of most philosophers and social scientists, so they ignore them. After all, the popularity of Marxism can partially be explained by its being simple enough for the average revolutionary, undergraduate, or revolutionary undergraduate to grasp and use rather than its claims to Truth, so a competing theory that is both hard to understand and even harder to apply is going to have trouble, regardless of its utility or veracity.

The social science triple of Popper, Lakatos, and Kuhn illustrates that the aforementioned analytical results have made their way slowly into mainstream philosophy and social science. Popper's post-war, anti-historical positivism held that statements and theories could not be proven true but could be demonstrated as false. This view resulted in an unstable and ultimately unworkable scientific climate. Lakatos loosened the analytic rules on falsifiability and held that theories could prove useful even if they had led to a few false results. Kuhn’s (1962) paradigms and scientific revolutions extended the views of Lakatos.

A.3 Rationality

So where does this leave us -- in an uncertain world of relativism? Certainly not. We're left with the knowledge that the world is a more complicated and subtle place than some, especially logicians, positivists, and philosophers, would have us believe. Lakatos states that criticisms of the form, "You put forward a complicated theory and one aspect of it proved false so the whole theory is false," are unhelpful. Of course debating such questions helps train the mind, but words and logic cannot capture the essence of existence. In a sense we have known this since Gödel told us so 70 years ago, but operationalizations and interpretations inevitably trail their motivating revelations.

Currently we see the brightest philosophy students voting with their feet and moving into cognitive science, an amalgam of philosophy, computer science, and experimental psychology. The reason why is simple: because these fields can provide testable insights into longstanding philosophical problems, primarily *rationality*, which lies at the root of so many intractable disagreements. Traditional philosophical notions of rationality are most clearly defined in the most analytic of the social sciences, economics. However, microeconomic definitions of rationality are axiomatic and do not pretend to portray how people really think, which is problematic. Moreover, maximizing one’s expected utility is possible in a heuristic, localized, temporally constrained sense, but to do so in an absolute, global sense is impossible because rationality is bounded (Simon 1983; Morecroft 1983). The analysis of rationality will advance to the extent that the way people actually think and interact with their environment is accurately portrayed.

This brings us to the conclusion, which I base on the work of Lakoff and Johnson (1999) who argue that traditional Western thought is methodologically characterized by three assumptions: that 1) we can know our own minds by introspection, 2) most of our thinking is literal, and 3) reason is disembodied and universal. Lakoff and Johnson, in contrast, maintain that 1) most thought is unconscious, 2) abstract concepts are mostly metaphorical, and 3) the mind is embodied (i.e., physical). This helps to explain the debate between proponents and opponents of *Limits to Growth* in that they are both espousing worldviews that are partially true. The ultimate question is this: Recognizing the source and motivation for the disagreement – that is, sharply differing worldviews based on very different assumptions – is there a way to move the debate forward? The purpose of this study is to show that system dynamics can do precisely that.

Appendix B. Duffing Oscillator Equations

```
X(t) = X(t - dt) + (dX) * dt
INIT X = 3

INFLOWS:
dX = Y
Y(t) = Y(t - dt) + (dY) * dt
INIT Y = 4

INFLOWS:
dY = forcing_function - (.05*Y) - X^3
forcing_function = 7.5*COS(time)
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