Structural Stability of the Political Economy

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Abstract

Recent events in the global economy have caused many writers to argue that the market is driven by animal spirits, by irrational exuberance or speculation. At the same time, the economic downturn has apparently caused many voters in the United States, and other countries, to change their opinion about the the proper role of government. In the introduction, we discuss the Enlightenment arguments of Condorcet, Adam Smith and David Hume about the nature of cooperation and moral sentiments, and more recent work in sociobiology that has been influenced by new ideas in evolutionary theory. We then consider models of chaos, with applications to climate change and economics, and then discuss the past influences of climate on human society, and particularly how agriculture developed during the "holocene", the past ten thousand years of benign climate. It is suggested that climate change is likely to bring about economic and political catastrophe.

1. Knowledge of Science and Society

1.1 Moral Sentiments

There have been speculations that it is no accident that the most important cosmologist after Ptolemy was Nicolaus Copernicus (1473 – 1543), born only a decade before Martin Luther. Both attacked orthodoxy in different ways.[1] Copernicus formulated a scientifically based heliocentric cosmology that dis- placed the Earth from the center of the universe. His book, *De revolutionibu orbium coelestium* (*On the Revolutions of the Celestial Spheres*, 1543), is of- ten regarded as the starting point of the Scientific Revolution. Moreover, in 1526 Copernicus also wrote a study on the value of money, *Monetae cudendae ratio*. In it Copernicus formulated an early version of the theory, now called Gresham's Law, that bad (debased) coinage drives good (non-debased) coinage out of circulation, Margolis (2002) noted that something very significant occurred in the years after Copernicus. His ideas influenced many scholars: the natural philosopher, William Gilbert, who wrote on magnetism in *De Magnete* (1601); the physicist, mathematician, astronomer, and philosopher, Galileo Galilei (1564 – 1642); the mathematician and astronomer, Johannes Kepler (1571 –1630).

Philosophiæ Naturalis Principia Mathematica (1687), by the physicist, math- ematician, astronomer and natural philosopher, Isaac Newton (1642 – 1726) is considered to be the most influential book in the history of science.[2] Margolis (2002) argues that, from about 1600, scholars learnt to look at scientific and social problems from different angles, and that within the next two hundred years this habit of mind became quite common, and was, in fact, the reason why the technological/ industrial revolution gathered apace in the eighteenth and nineteenth centuries. After Newton, a few scholars realized that the universe exhibits laws that can be precisely written down in mathematical form. Moreover, we have, for some mysterious reason, the capacity to conceive of exactly those mathematical forms that do indeed govern reality. We believe that this mysterious connection between mind and reality was the basis for Newton's philosophy. While celestial mechanics had been understood by Ptolemy to be the domain most readily governed by these forms, Newton's work suggested that *all* reality was governed by mathematics.

We shall call the underlying hypothesis entertained by these scholars *the universality of mathematics.* Major universal mathematicians include the Scot, James Maxwell (1831–1879), the Frenchman, Henri Poincar (1854–1912), the German, Albert Einstein (1879–1955), and the Englishman, Stephen Hawking (born 1942).[3] Hawking and Mlodonow (2010) argue for this universal principle, citing its origins in Pythagoras (580 BCE to 490 BCE), Euclid (383 -323 BCE and Archimedes (287-212 BCE), and the recent developments in mathematical physics and cosmology. They present a strong form of this principle, called *model-dependent realism,* arguing that it is *only* through a mathematical model that we can properly perceive reality. Without the application of this universal mathematics, our society would be quite different and much poorer.

Jardine (1999,2008) discusses the scientific innovations by Hooke and Huygens in the period round the glorious revolution, while Appleby (2010) discusses the technological changes wrought by Arkwright, Hargreaves, and Crompton soon after. There is still controversy over whether the rapid technological and economic transformations that we experience today are the consequence of the development of science itself, or the result of the institutional changes in the political economy that started in Great Britain in the 1600's.[4] Ferris (2010) argues that the political and economic innovations of the time were linked to these developments in mathematics and science. The influence of Newton can perhaps be detected in the work of the philosopher, mathematician, and political scientist, Marie Jean Antoine Nicolas de Caritat, Marquis de Condorcet (1743 – 1794), known as Nicolas de Condorcet. His work in formal social choice theory (Condorcet ([1785],1994) was discussed in Schofield (2006) in connection with the arguments about democracy by Madi- son and Jefferson.

This work also discussed the influence of the work on Moral Sentiment by the Scottish Enlightenment writers, Francis Hutcheson (1694– 1746), David Hume (1711–1776), Adam Smith (1723–1790) and Adam Ferguson (1723–1816). Between Copernicus and Newton, the writings of Thomas Hobbes (1588 – 1679), Ren Descartes (1596– 1650), John Locke (1632– 1704), Baruch Spinoza (1632– 1677), and Gottfied Liebnitz (1646– 1716) laid down foundations for the modern search for rationality in life.[5] Hobbes was more clearly influenced by the scientific method, particularly that of Galileo, while Descartes, Locke, Spinoza, and Liebniz were all concerned in one way or another with the imperishability of the soul.[6] Liebniz in particular was concerned with an [E]xplanation of the relation between the soul and the body, a matter which has been regarded as inexplicable or else as miraculous. Without the idea of a soul it would seem difficult to form a general scheme of ethics.[7] Indeed, the progress of science and the increasing secularization of society over the last century led Ferguson (2002) to note that [l]oss of faith in [the British Empire] often went hand in hand with loss of faith in God.

1.2 Beliefs

In the 1920's and 1930's, after World War I and the devastation wrought by the application of science and technology, a general fear become prominent that civilization would fall, just as the Ottoman, Russian and Habsburg empires had fallen, soon to be followed by the British Empire.[8] These fears were exemplified first by Spengler's *Decline of the West* (1918, 1922) and later by Toynbee's *Study of History* (1934). Ferguson (2006) quotes Spengler to the effect that The masses will accept with resignation the victory of the Caesars. Mead (2007) suggests, in contrast, that "it is to a dynamic religion rather than secularization that we must look for explanations of the Anglophone ascendency [of the American empires]."[9] Indeed, much recent work substantiates the ideas of the Scottish moral philosophers, and the later suggestions of Darwin (1871), proposing that we all have an innate sense of moral values. Ober and Macedo (2006) suggest that moral goodness is something real, and does not need to be based on the notion of a trancendent soul.[10]

The last twenty years has seen a growing literature on a game theoretic analysis of the evolution of social norms to maintain cooperation in prisoners' dilemma like situations. Gintis (2000, 2003), for example, provides evolutionary models of the cooperation through strong reciprocity and internalization of social norms.[11] The anthropological literature provides much evidence that, from about 500KYBP years ago, the ancestors of *homo sapiens* engaged in cooperative behavior, particularly in hunting and caring for offspring and the elderly.[12] On this basis we can infer that we probably do have very deeply ingrained normative mechanisms that were crucial, far back in time, for the maintenance of cooperation, and the fitness and thus survival of early hominids.[13] These normative systems will surely have been modified over the long span of our evolution. A related literature deals with various detailed aspects of how these norms may have evolved.[14] Some of this literature is also based on evolutionary theory[15],

some from neuroscience[16], some from child development[17] and some from the study of primates .[18] Hauser (2006) argues that there is a deep structure to moral values, akin to the notion of a template in language[19] while Deacon (1997) argues instead that language and the brain co-evolve. Since language evolves very quickly (McWhorter, 2001; Deutcher, 2006), we might also expect moral values to change fairly rapidly, at least in the period during which language itself was evolving. In fact there is empirical evidence that cooperative behavior as well as notions of fairness vary significantly across different societies.[21] While there may be fundamental aspects of morality and "altruism," in particular, held in common across many societies, there is varia- tion in how these are articulated. Gazzaniga (2008) suggests that moral values can be described in terms of various *modules*: reciprocity, suffering (or empathy), hierarchy, in-group and outgroup coalition, and purity/ disgust.

These modules can be combined in different ways with different emphases. Currently this literature lacks a fundamental unifying theoretical structure, although the earlier work by George Price ([1971], 1995) gave a formal stochastic model relating fitness to traits that can be used to study selection in any evolving process, including economic development[22] Binmore (2005, 2007) makes a number of very relevant comments on norms and culturally determined values, on the basis of notions from evolutionary game theory.[23] The most important point is that norms can be seen as particular kinds of equilibrium selection mechanisms that are generated by the nature of the technology that the society has developed, and the enviroment in which it is located. So hunter-gatherer societies will tend to exhibit equity or egalitarian share and effort norms.[24] Agricultural, or *limited access societies*, of the kind discussed by North, Wallis and Weingast (2009), will focus on norms associated with hierarchy, power, honor and obedience. *Open access societies* will focus on norms of freedom, fair play and merit.[25] The industrial development that occurred in Britain and the US in the past brought these equity norms into contest with economic principles of "efficiency" and the free market.[26] The recent technological changes have exacerbated economic inequality, particularly in the US.[27]

These different normative beliefs about the proper balance between efficiency and equity are just as important as preferences in affecting political choice. In any polity the underlying moral beliefs can be fairly heterogenous, reflecting these different emphases on efficiency, equality, freedom, and hierarchy.[28] There is still no generally accepted theory about how these beliefs are propagated and transformed in a society. It has been suggested that they can be regarded as "memes," acting like genes, mutating and multiplying under selection pressure.[29] Indeed scientific notions, such as that of "meme" itself, as well as moral principles can be thought of memes.[30] Bikchandani et al.(1992, 1998) write about *fads* and *information cascades*. Schofield (2006) introduced the notion of belief cascades in an attempt to capture the idea that such changes of political beliefs can be the result of new theories about how the world works, constructed in order to deal with the quandaries that the society faces.[31]

As we have suggested above, political beliefs will be affected by expectations about the future, as well as interpretation of the past. The collapse of the Soviet Empire in 1989 first brought about a sense of relief, as exemplified by the notion of the triumphant "end of history" of Fukayama (1992), and a period of stability and globalization. Below, we refer to this as the *holœne*, lasting most recently from about 1990 until 2001. However, American hegemony was short-lived. The "Clash of Civilizations" (Huntington, 1998) after 2001, the recent recession of 2008/9, and the current fears over the effects of climate change and international disorder, remind us of the earlier fears, in the inter war years, about the over-rapid development of science and the possibility of civilization's collapse through war. In hindsight, these earlier fears in the 1930's over future war were entirely justified.

2 Uncertainties

Many authors, from Paul Kennedy (1987) on, have discussed the similarities and differences between the Roman, British and American empires in terms of military over-reach and hubris.[32] Indeed, Ferguson (2005) uses an interesting typology of empire, distinguishing between those that are autocratic, aristocratic, oligarchic or democratic, and whether they are based on the prncipal factors of land, labor or capital. While there are ~~obvious differences between~~ these empires, Ferguson (2010) also suggests that the American empire, like earlier ones, may collapse in a chaotic fashion, possibly bringing about catastrophe. He notes that the total US federal debt increased from $5 trillion in 1992 to $7 trillion (about 70% of GDP) in 2000, to $17 trillion (about 117% of GDP) in 2010. In fiscal year 2000 there was a federal surplus of $236 billion, which by 2004 had become a deficit of about $520 billion, partly because of the Bush tax cuts.

The estimated federal deficit for the fiscal year ending Sept. 30, 2010, is $1.47 trillion, over 10% of GDP. Stiglitz and Bilmes (2008) laid part of the blame for the increasing federal deficit on the Iraq war, citing a total estimated past and future cost of $3 trillion.[33] Like Kennedy and Ferguson, Bacevich (2010) develops this theme of military over-reach, suggesting that the US has become wedded to permanent war. He argues that the recent crisis, and the problem of debt, has made this imperial military and economic strategy impossible for the US to maintain. In terms of economic decline, the trade deficit of the United States with China increased from $103 billion in 2002 to $268 billion in 2008, though it dropped to $227 billion in 2009. China now holds about $900 billion in US debt, followed by Japan with $800 billion. The rest of the US debt is spread between OPEC, Brazil, Hong Kong and Taiwan. We seem to be entering a new type of multipolar world, with no hegemon, and potential conflicts between regional powers such as China, India, Brazil, as well as the oil rich states of the Middle East and Russia.[34] The 1990's may, in the future, seem like an economic holocene, maintained by the economic and military hegemony of the United States. An important aspect of this dominance lay in the belief in the "soft power" of the US, namely the validity of the principles of democracy and capitalism.[35] The double shock of 2001 and the crisis of 2008/9 has brought this period to an end, and it may well be that without such a hegemon, political *and* economic instability will be exacerbated. In recent years, fears over an uncertain future have been have been com- pounded by changes in our understanding about how the world, and society really work. First, at the level of the logic of science, Prigogine (1996) has used chaos theory to argue against the predictability and determinism of a Newtonian universe. Von Hayek (1974) made a related point, in his Nobel lecture, about the difference between economics and what he considered to be the way natural science works:

> While in the physical sciences it is generally assumed, probably with good reason, that any important factor which determines the observed events will itself be directly observable and measurable, in the study of such complex phenomena as the market, which depend on the actions of many individuals, all the circumstances which will determine the outcome of a process... will hardly ever be fully known or measurable.

For Milton Friedman (1953) on the contrary, it was irrelevant whether economic theory made unrealistic assumptions, as long as it worked. But the recent recession strongly suggests that economic theory just does not work. The collapse of belief in the logic of economic theory is exemplified by the confession of Alan Greenspan, former chairman of the Federal Reserve, to Congress in 2008, when asked whether his ideology about market equilibrium was right, and working, replied that he was shocked to learn that it was wrong.[36] He has also commented that "our current understanding of the future is extremely limited." In the face of this uncertainty about the future, we argue that it behoves us to attempt to create an ethical basis for our actions when they have such possibly dire consequences. There may be disagreements about an ethical foundation for society, with a pure free market orientation at one pole, and an extremely egalitarian focus at the other. Almost all people believe in some version of propinquity , my family, my neighborhood, my country. On the other hand, there is belief that the future, our children, and future generations, should be protected from our greed.

As an illustration, both Jefferson and Condorcet argued that debt or other liabilities should not be incurred if they could not be paid off in a generation. (Their argument was that in about a generation of 20 years, half the population would have changed through birth and death.) This is a version of "intergenerational utilitarianism" proposed by Collier (2010). This principle asserts that we should be "fair" towards the future, by taking into account the expected overall utility of future generations.[37] A natural consequence of this principle is that we should avoid destroying the world we live in for short term gain. Note that this is a utility principle, not an income principle. If climate change is expected to have greatest impact on the poor, in Africa say, then this principle implies that costs should be borne in the developed economies to offset the likely enormous utility costs of the poor in the future. One aspect of this calculation is the appropriate discount parameter to use. Collier suggests that if we do choose to burden the future, then we should lay aside assets to cover the anticipated future costs.

Relatively risk free assets such as U.S.Treasury bonds give about 3 to 4% return, so this can be used to infer the appropriate transfer to the future. Posner (2005) estimates that the cost of climate change could reach about $8 trillion a year, so discounted at 3%/annum would give a total cost of about $65 trillion. If we follow Collier (2010) and do not discount the future then the total cost would be astronomical. An ancillary calculation made by Collier is that when we deplete non-renewable natural resources, oil, minerals etc. then we should also lay aside economic assets, namely investment capital, to cover the fact that these resources will not be available to the future. Finally, carbon, generated by our own economic activity, is a burden, a negative externality, that will affect the future, through its impact on climete. One way to cover the transfers to the future would be through a carbon tax. Since the developed economies currently produce the bulk of CO_2,a carbon tax would have the beneficial effect of somewhat reducing consumption, in these economies, of carbon based fuels, and this would make non carbon fuels more viable. Collier suggests a tax of $40/ton of carbon emitted.[38] Such a tax has the advantage that if estimated costs to the future rise, then tha tax rate can be adjusted. One further aspect of this way of dealing with the externality is the matter of uncertainty. There is a great deal of uncertainty at present, over the effects of economic activity. Even with the mathematical models of climate change that we discuss below, this uncertainty will persist.

If our activities cause even more uncertainty over the consequences of our actions, then we should further compensate the future. Below, we discuss the work of Stern, who argues that we should be extremely risk averse over climate effects. Since future generations will face the costs of our decisions, we too should be uncertainty averse, and devote resources to the attempt at gauging these costs. One of the problems with dealing with climate change is that it concerns decision making in what are known as "large worlds." Models of decision making work well in "small worlds" where probabilities can be estimated. Chilichilnisky (2009, 2010) provides the beginning of a theory of decision-making in such "large worlds" involving uncertain, potentially disasterous "black swan" events.[39] In our opinion, uncertainty about the future resides in the possibility that the dynamic systems that will determine our future are, in fact, *chaotic*. From the time of Newton to Laplace, the dominant notion in science was *determinism.* In the developing social sciences and economics, statistics provided a way of interpreting and controlling events. But the efforts to extend the simple Newtonian model of celestial mechanics by Poincar in the late nineteenth century showed that apparently deterministic physical systems could be deeply chaotic or non-predictable.[40]

An essentially mathematical theory that has been developed in the few decades or so is *complexity or chaos* theory, dealing with the non-deterministic properties of dynamic systems.[41] This theory is only a few years old but it already forces us to rethink habits of mind about how the world and society work. One area where this theory has proved of use is in understanding the complex positive and negative feedback mechanisms that govern climate and its effect on human evolution. Section 3 suggests how celestial mechanisms to do the Earth's orbit interact with geological processes on the planet to affect the CO_2 level. For example, the uplift of the Tibetan plateau has acted to remove CO_2 over the last 40 million years, inducing oscillations between glacial and interglacial periods. The current ice age, the Pliocene-Quaternary glaciation, started about 2.58 million years ago during the late Pliocene. The planet generally became drier during this ice age, and the ancestors of our species,*Homo habilis* (from *2.5* MYBP*) and Homo erectus* (from 1.8 MYBP), adapted to the new savannah conditions in Africa.

Remains of Homo erectus have been found in Java dating to 1.6 MYBP. In Section 1.1 we have mentioned the extensive literature on the evolution of these early hominids. It has been argued that *Homo erectus* included meat in its diet, and used fire, thus increasing the energy available to became an efficient and cooperative predator.[42] Mitochondrial analysis from modern humans suggests a common ancestor in Africa about 200KYBP.[43] Equipped with language, a system of moral values, associated with cooperation, and a technology of increasingly sophisticated tools, this early hunter gatherer spread throughout the planet. It is thought that there were two conduits out Africa, about 70KYBP, one from the Horn of Africa and one across the Sinai peninsula into Asia. As we discuss below in Section 4, from about 90 to 10 KYBP, climate became highly unstable. Without our ancestors' braininess, language and culture, the uncertainty induced by climatic chaos could have driven *Homo sapiens* to extinction. Indeed, it has been argued that an eruption in Sumatra about 70KYBP induced an instant ice age and almost killed off all *H.sapiens.*

It may well have finished off *H. erectus.*[44] The human population is estimated to be between 250,000 and 500,00 in 62KYBP, slowly increasing to about 6 million in 12KYBP, at the end of the ice age. Climatic amelioration at this beginning of the *Holocene* in 12KYBP meant warm, wet conditions over much of Eurasia allowing for the transformation of hunter gatherer society to agricultural communities in the Middle East. After the transition, human population increased to about 60 million in 3KYBP (the beginning of the bronze age) and then to about 240 million in 2KYBP. Farming appeared in the Fertile Crescent about 11.5KYBP with wheat, barley, then peas and lentils. It spread to Egypt by 9.5KYBP, and had independent origin in China and India about the same time, but much later in the New World (Diamond, 1997). Pastoral agriculture appeared about the same time:

goats were tamed in Iran by 12KYBP, sheep in Iraq by 9KYBP, and various breeds of cattle in the middle east and India by 8KYBP. Cochran and Harpending (2009) argue that this population explosion was coupled with both cultural and genetic transformations. In particular, the change from hunter gatherer society to agriculture and "closed access society" was associated not only with a dramatic increase in population and "total economic product," but also in inequality, and the division of society into poorly fed peasants and military and technological elites.[45] The induced Malthusian constraint meant that the "real wage" tended to decline except at catastrophic times when population crashed because of plague, as in the fourteenth century.[46] As discussed in Section 1.1, from about 1600 our very braininess triggered a scientific explosion in the development of mathematical languages which allowed for the deeper analysis of the world and society.

The beginnings of the agricultural and industrial revolutions in the United Kingdom from 1700 on and then later in the United States, and the transition to "open access societies" triggered rapid economic and population growth, but also initially caused an increase in inequality.[47] This was reversed from about 1860, and further economic growth induced swift changes in the balance between capital and labor during the late nineteenth and early twentieth centuries. In 1860, GDP/capita in both the UK and the US was about $2800, rising in parallel to about $5500 by 1914, and staying roughly constant during the times of turmoil until the 1930's. After World War II, GDP/capita started to rise rapidly from $9.5K in 1950 to $30K by 2003 in the US, and from $7K to $21K in the UK.[48] Until about 1970, this pattern of growth seems to have lessened the degree of inequality in the developed economies.[49]

We suggest that the period from 1990 to the present can be seen as an economic holocene. In the same way we may see the previous long periods of growth in these two periods from 1860 to 1914 and from 1950 until about 2006 as *economic and political holocenes.* Both periods were characterizd by hegemonic leadership, first by Great Britain and then by the United States. Maddison estimates that world population grew from a billion in 1820 to about 1.8 billion in 1914. For this most recent period from 1950, world population grew from 2.5 billion to 6.8 billion. The population growth rate increased from about 1.5% in 1950 to over 2% in 1971, and has gradually fallen to 1.1% at present. This recent population growth has induced a number of changes in the world political economy.

First, technological development has shifted the balance of economic power both within developed economies and between the developed and less developed economies. Second, inequality within the developed polities has tended to increase from about 1970, partly because of the premium put on technological skill and partly due to the change in the age distribution of the population. This has been exacerbated by the transfer of manufacturing comparative advantage from developed to less developed countries, particularly China and India. As commented on above, these global changes have made political economic conflict much more difficult to resolve, and have suggested similarities between the present and the end of the last economic holocene in 1914. It is unlikely that we face anything like World War I, but it does now seems that the world and our society are much more complex than implied by the various social theories that were developed to facilitate growth in the past. It is very unclear what triggered the transition to open access society after 1700, to be followed by the disorder of the interwar period and then the astonishing changes after 1950.[50] We have suggested that there are elements of the world and society, such as climate and the pattern of economic development, that are chaotic. This presents us with quandaries about how to make decisions with regard to the future. The most mathematical of our theories about society, namely general equilibrium, may also be deeply flawed, and we may need to think again about how to orchestrate our institutions to guard against risk. Since chaos and uncertainty are inextricably linked, a discussion of varieties of chaos can suggest to us why the future is so uncertain, and perhaps provide a better understanding of how to deal with the externalities that we are currently imposing on future generations.[51] The next section discusses applications of chaos in the market, in weather and in the heavens.

3 Chaos in the Market, in Weather and in the Heavens

John Maynard Keynes's work, *The General Theory of Employment, Interest and Money* (1936) was very probably the most influential economic book of the twentieth century. *The General Theory* is , in a sense, a continuation of Keynes's earlier writing on the foundation of probability, completed in the period 1906 to 1914, and published eventually as the *Treatise on Probability* (1921). In the *Treatise*, Keynes viewed probability as a degree of belief.[52] writing:

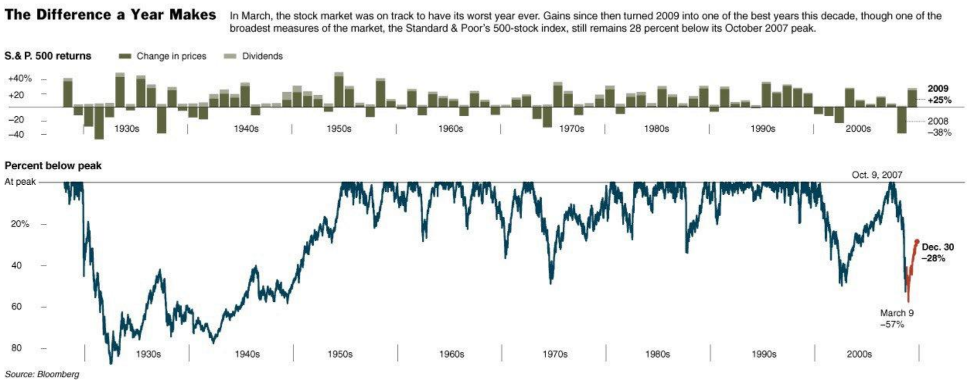
> [T]he old assumptions, that all quantity is numerical and that all quantitative characteristics are additive, can no longer be sustained. Mathematical reasoning now appears as an aid in its symbolic rather than its numerical character. I, at any rate, have not the same lively hope as Condorcet, or even as Edgeworth, "Eclairer le Science morales et politiques par le flambeau de l'Algebre."

Macro-economics as it is practiced today tends to put a heavy emphasis on the empirical relationships between economic aggregates, while micro-economics emphasizes the logic of equilibrium and market efficiency. Keynes' views, in the *Treatise*, suggest that he was impressed neither by econometric relationships nor by algebraic manipulation. Moreover, his ideas on "speculative euphoria and crashes would seem to be based on an understanding of the economy grounded neither in econometrics nor algebra but in the qualitative aspects of its dynamics.

It has been argued (Schofield, 1999) that a dominant core belief, the *economic equilibrium hypothesis*, had won universal acceptance among policy makers in the aftermath of the chaotic events of the 1970's. The International Financial Crisis of 1997-1998, involving Russia, Indonesia, Malaysia, and many countries in Latin America, indicated that the global economy faced a fundamental quandary derived from the realization that this core belief was wrong. A resolution of this quandary could be based on accepting that Keynes was correct in his understanding of the global economy. While commodities markets, governed by risk, might well display equilibrium, asset markets, governed by speculation, do not. For Keynes, asset markets display fundamental uncertainty. The events of the late 1990's indicated that fundamental reform of international institutions was necessary to avoid chaos.

The crisis of 1997-1998 was followed shortly after by the collapse of the dot.com bubble. Figure 1 shows the magnitude of changes in the US stock market in the long period from the 1920's to the present (the figure normalizes the changes by setting all peaks to unity). It is noticeable that the fall from a peak in the Dow of 11,723 on January 14, 2000, to its next low of 7,286 on October 9, 2002, was followed by a peak of 14,164 on October 9, 2007. The next low was 6,547 on March 9, 2009. These violent oscillations are compatible with Hyman Minsky's theory of market volatility, based on Keynsian uncertainty (Minsky, 1975, 1986).. Minsky's argument is that periods of economic growth eventually lead to irrational beliefs about the degree of risk embedded in the market. Increasing risk taking leads to a bubble, and this eventually collapses when the true level of risk becomes apparent. Minsky's work therefore denies the core principle of market efficiency associated with the equilibrium hypothesis.

Figure 1: Chaotic stock market prices 1930-2009 (Source: New York Times, Dec 31, 2009)



The collapse of the global property/housing bubble from late 2006 destroyed trillions of dollars of assets, not just in the US but worldwide, and almost destroyed the global market itself. Rapidly rising unemployment showed that disorder in financial markets could have real macroeconomic effects. Many theories have been put forward recently to account for this bubble. One of these is that China's mercantilism meant that its purchases of dollar assets, to maintain its cheap currency, provided cheap money to US consumers, fueling the bubble and US economic growth (Ferguson,2008). While there is some truth to this argument, it does not provide a basis for understanding the periods of high and low volatility apparent from Figure 1. In this essay, I shall focus on the idea of chaos that underlies Keynes's arguments about uncertainty. To do this I shall first discuss the economic equilibrium and efficient market hypotheses. The idea of chaos first occurred in constructing models of the weather, climate and celestial mechanics, and I shall use such models to give an idea of what chaos is all about.

In discussing climate, I shall argue that our civilization developed during a period known as the holocene. I conjecture that the prior period of market stability resembles the holocene, and we should prepare ourselves for a future of increasing chaos. How we might defend against this future chaos will depend on building dynamical models of the econony and climate that are not based on false equilibrium arguments, but incorporate at least some of the complex feedback mechanisms that we now know govern our society. First consider a thought experiment to about the global economy. There must be local periodicities due to climatic variation. Since hurricanes and monsoons, *etc.* effect the economy, one would expect small chaotic events. More importantly, however, some of the behavior of economic agents will be based on their future expectations about the nature of economic growth, *etc.* Thus one would expect long term expectations to affect large scale decisions on matters such as investment, fertility etc. It is evident enough that the general equilibrium (GE) emphasis on the existence of price equilibria, while important, is probably an incomplete way to understand economic development.

In particular, GE theory tends to downplay the formation of expectations by agents, and the possibility that this can lead to unsustainable “bubbles.” It is a key assumption of GE that agents’ preferences are defined on the commodity space alone. If, on the contrary, these are defined on commodities *and* prices, then it is not obvious that the Arrow Debreu (1954) Theorem can be employed to show existence of a price equilibrium. More generally one can imagine energy engines (very like hurricanes) being generated in asset markets, and sustained by self-reinforcing beliefs about the trajectory of prices. It is true that modern decentralised economies are truly astonishing knowledge or data- processing mechanisms. From the perspective of today, the argument that a central planning authority can be as effective as the market in making “rational” investment decisions is very controversial. Hayek’s “calculation” argument used the fact that information is dispersed throughout the economy, and is, in any case, predominantly subjective. He argued essentially that only a market, based on individual choices, can possibly “aggregate” this information (Hayek, 1945). Recently, however, theorists have begun to probe the degree of consistency or convergence of beliefs in a market when it is viewed as a game. It would seem that when the agents “know enough about each other , then convergence in beliefs is a possibility In fact the issue about the “truth-seeking capability” of human institutions is very old and dates back to the work of Condorcet . Recent work suggests that there may be belief cascades or bubbles, which generate multiple paths of beliefs which diverge away from the “truth.” (Bikhchandani, et al.1992, 1998).

3.1 Market Chaos

The laws of motion of an economy should be derived from modeling individuals’ “rational behavior as they process information, update beliefs and locally optimize. As Akerlof and Shiller argue,

> the business cycle is tied to feedback loops involving speculative price movements and other economic activity — and to the talk that these movements incite. A downward movement in stock prices, for example, generates chatter and media response, and reminds people of longstanding pessimistic stories and theories. These stories, newly prominent in their minds, incline them toward gloomy intuitive assessments. As a result, the downward spiral can continue: declining prices cause the stories to spread, causing still more price declines and further reinforcement of the stories.(Akerlof and Shiller 2009)

At present it is not possible to construct such a micro-based macro-economy because the laws of motion are unknown. Nonetheless, just as simulation of global weather systems can be based on local physical laws, so may economic dynamics be built up from the local “rationality of individual agents. However, the GE models discussed in this paper are based on the assumption that the political economic world is contractible, that is, it has the topological characteristic of a ball. This seems an unlikely assumption.[53] Although the total set of resources may well be bounded, it does not appear to be the case that technological possibilies are similarly bounded. Indeed, the Enlightenment argument between Malthus and Condorcet seems, at least in the developed world, to have been carried by the optimistic Condorcet. However, the less developed world, particularly Africa and parts of the Middle East, faces Malthusian constraints that engender economic and political disorder (Condorcet [1795]. 1955) and Malthus, [1798], [1830]).

North (2005) argues that the growth of the developed world is due to its sophisticated institutions, what Kling and Schultz (2009) call “protocols,” namely the social ability to solve social and economic problems.[54] Although we might have reason to be optimistic about technological advance, recent economic events have caused concern about the validity of current economic theory. Since our social protocols are crucial to our society, it is imperative they they work in an efficient manner. This concern has led to an extensive literature, in the last few years, dealing with the efficiency of our market protocols, the theory of efficient markets. This literature discusses the nature of herd instinct, the way markets respond to speculative behavior and the power law that characterizes market price movements.[55] Some of these analyses are based on a version of the market equilibrium theorem. In fact, much of the work on efficient markets is based on the Black-Scholes partial differential equa- tion used to price options.[56]. The recent collapse of the economy suggests that this equation is subject to chaotic singularities, whose qualitative nature is not understood. As discussed above, Minsky’s interpretation of Keynes’s general theory focuses on the proposition that asset pricing is subject to an extreme degree of uncertainty. The underlying idea is that individuals do not know the true probability distribution on the various states of the world, but only have personal probability distributions, in the sense of Savage (1954).

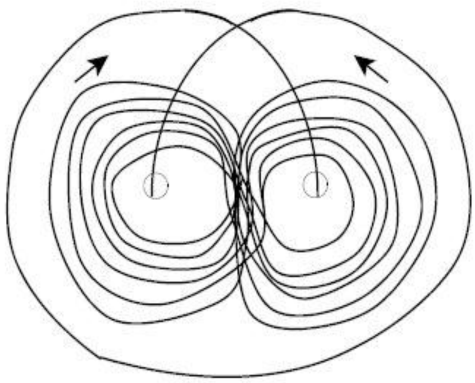
They make stochastic choices on the basis of this personal uncertainty. Agents may also differ widely in how they treat "black swan" low probability events. Since investement decisions are based on these uncertain evaluations, and these are the driving force of an advanced economy, the flow of the market can exhibit singularities, of the kind that recently nearly brought on a great depression. These singularities are time-dependent, and can be induced by endogenous belief-cascades, rather than by any change in economic or political fundmentals.[57]

More abstractly, the space in which economic and political behavior occurs may be thought of as a "manifold" of very high dimension. While GE asserts that there are equilibria , these will depend on the dynamical domain in which they are defined. These domains are separated by singularities, where the qualitative nature of the system may be radically transformed. To illustrate this point by the stock market, shown above in Figure 1, the flow does not look like a slowly changing equilibrium, responding to exogenous changes in population and resources. A period of relative stability, or low volatility, as in the 1990's, would give a false impression of risk prior to the singularity in 2000. This stable period was followed by collapse, then euphoria, then by collapse again, then the current partial recovery. The period of disorder associated with such a singularity we can call "chaos."[58]

3.2 Chaos in Weather

"Empirical chaos" was probably first discovered by Lorenz (1963,1993). He found that slight changes in the coefficients of a simple system, with three variables and three parameters, used to model the weather, gave rise a qualitatively different dynamical process. Figure 2 gives a pictorial representation of the dynamical system he found, the so-called "butterfly."

Figure 2: The "butterfly"



Given that chaos can be found in such a simple meteorological system, it is worthwhile engaging in a thought experiment to see whether "climatic chaos" is a plausible phenomenon. Weather occurs on the surface of the earth, so the spatial context, or "geosphere," is the two-dimensional sphere, the surface of the earth, S^2 I, where I is an interval corresponding to the depth of the atmosphere. Purely theoretical arguments show that a certain kind of dynamical system on S^2 I will exhibit a singularity. For example, the impact of different weather systems can be seen as a singularity. But the effect of their impact will often be indeterminate. The system of plate tectonics occurs in the "lithosphere" also in S^2 I, so volcanoes can also be seen as singularities. Earthquakes and volcanoes on the tectonic boundaries are locally chaotic because of the non-linearity of the dynamical system that governs their behavior.[59]

The domain of the dynamical system near a singularity can be called a portal, and it is within a portal thatthe dynamics becomes chaotic. Climate is affected by temporal periodicities, induced by the orbit of the earth round the sun and wobbles in the earth's rotation.[60] In addition there are spatial periodicities or closed orbits in the geosphere. Chief among these must be the jet stream and the oceanic orbit of water from the southern hemisphere to the North Atlantic (the Gulf Stream) and back. The most interesting singularities are the hurricanes generated each year off the coast of Africa and channeled across the Atlantic to the Caribbean and the coast of the U.S.A. Hurricanes are self-sustaining heat machines that eventually dissipate if they cross land or cool water. It is fairly clear that their origin and trajectory is chaotic. While the topological structure of the geosphere allows us to infer the existence of a singularity, understanding weather, and more generally, climate itself, involves the analysis of an extremely complex dynamical system that is affected by periodicities in the solar system. We now turn briefly to the notion of structural stability and chaos in the heavens.

3.3 Celestial Chaos

When Galileo Galilei turned his telescope to the heavens in August, 1609, he inaugurated the modern era in science. In his *Sidereal Messenger* he wrote of the myriad stars in the milky way, the moons of Jupiter, each at a different period and distance from Jupiter. Jupiter's moons suggested it was a planet just like the earth. Moreover the phases of Venus also suggested that it was a planet orbiting the Sun. These observations, together with Kepler's empirical "laws"on planetary orbits made it clear that the Copernican heliocentric model of the solar system was not just a mathematical theory but a truth. Galileo waited 22 years before publishing *Dialogue concerning the Two Chief World Systems, Ptolemaic and Copernican,* for fear that he would be accused of heresy by the Church. Indeed, in 1633, he was found guilty of "vehement suspicion of heresy*"* and spent the years until his death under house arrest, but writing *Two New Sciences* (1638). Within fifty years Newton published *Philosophiae Naturalis Principia Mathematica*, giving a mathematical model of physical reality, including celestial mechanics that provided the theoretical foundations for Kepler's Laws.[61]

Even with the Newtonian mathematical model, it was unclear whether the solar sytem was "structurally stable". Although it was possible to compute the orbit of a single planet round the sun, the calculation of the influence of many planets on each other seemed technically difficult. Could these joint influences cause a planet to slowly change its orbit, perhaps causing it to spiral in to the sun? Structural stability for the orbital system of the planets means that the perturbations, caused by these interactions, do not change the overall dynamic system. The failure of structural stability means that a slight perturbation of the dynamical system induces a change in the qualitative characteristics of the system. As in the previous discussion, we can use the term "chaos" to refer to this breakdown. It is only in the last twenty years or so that the implications of "chaos" have begun to be realized. In a recent book Kauffman commented on the failure of structural stability in the following way.

> One implication of the occurrence or non-occurrence of structural stability is that, in structurally stable systems, smooth walks in parameter space must [result in] smooth changes in dynamical behavior. By contrast, chaotic systems, which are not structurally stable, adapt on uncorrelated landscapes. Very small changes in the parameters pass through many interlaced bifurcation surfaces and so change the behavior of the system dramatically. (Kauffman, 1993)

It is worth mentioning that the idea of structural stability is not a new one, though the original discussion was not formalized in quite the way it is today. The laws of motion written down by Newton in *Principia Mathematica* could be solved precisely giving a dynamical system that for the case of a planet (a point mass) orbiting the sun. However, the attempt to compute the entire system of planetary orbits had to face the problem of perturbations. Would the perturbations induced in each orbit by the other planets cause the orbital computations to converge or diverge? With convergence, computing the orbit of Mars, say, can be done by approximating the effects of Jupiter, Saturn perhaps, on the Mars orbit. The calculations would give a prediction very close to the actual orbit. Using the approximations, the planetary orbits could be computed far into the future, giving predictions as precise as calculating ability permitted. Without convergence, it would be impossible to make predictions with any degree of certainty. Laplace in his work *M canique C leste* (1799-1825) had argued that the solar system (viewed as a formal dynamical system) is structurally stable (in our terms).[62]

Consistent with his view was the use of successive approximations to predict the perihelion (a point nearest the sun) of Haley's comet, in 1759, and to infer the existence and location of Neptune in 1846. Structural stability in the three-body problem (of two planets and a sun) was the obvious first step in attempting to prove Laplace's assertion. In 1885 a prize was announced to celebrate the King of Sweden' s birthday. Henri Poincare submitted his entry "Sur le probl me des trois corps et les Equations de la Dynamique." This attempted to prove structural stability in a restricted three body problem. The prize was won by Poincare although it was later found to contain an error. His work on differential equations in the 1880s and his later work, *New Methods of Celestial Mechanics* in the 1890's, developed qualitative techniques (in what we now call differential topology). The Poincare conjecture, that "a compact manifold, with the same algebraic invariants as the three-dimensional sphere, is indeed a three sphere" was one of the great unproven theorems of the twentieth century. The theorem has recently been proved by Grigori Perelman.[63] The earlier efforts to prove this result has led to new ideas in topological geometry, that have turned out, surprisingly, to have profound implications for a better understanding of general relativity and the large scale structure of the universe.

Our physical universe is a three dimensional manifold, probably bounded and thus compact. The Ricci flow on this manifold is given by a certain partial differential equation. This equation is a way of characterizing the curvature of geodesics on this manifold. The equation has a deep relationship with the topological structure of the universe. Perelman's proof depends on understanding the nature of singularities associated with this equation. One of the notions important in understanding structural stability and chaos is that of *bifurcation*. Bifurcation refers to the situation where a particular dynamical system is on the boundary separating qualitatively different systems. At such a bifurcation, features of the system separate out in pairs. However Poincar also discovered that the bifurcation could be associated with the appearance of a new solution with period double that of the original. This phenomenon is central to the existence of a period-doubling cascade as one of the characteristics of chaos. Near the end of his *Celestial Mechanics*, Poincar writes of this phenomenon:

> Neither of the two curves must ever cut across itself, but it must bend back upon itself in a very complex manner ...an infinite number of times.... I shall not even try to draw it...nothing is more suitable for providing us with an idea of the complex nature of the three body problem.(Galison, 2003, p.74

Although Poincar was led to the possibility of chaos in his investigations into the solar system, he concluded that though there were an infinite number of such chaotic orbits, the probability that an asteroid would be in a chaotic orbit was infinitesimal. Arnol'd showed in 1963 that for a system with small planets, there is an open set of initial conditions leading to bounded orbits for all time.[64] Computer simulations of the system far into time also suggests it is structurally stable.[65] Even so, there are events in the system that affect us and appear to be chaotic (perhaps catastrophic would be a more appropriate term). It is certainly the case that the "N-body system" can display exceedingly complex, or chaotic phenomena.[66] Although space is three dimensional, the Einsteinian universe also involves time, and the behavior of geodesics near space-time singularities may also be very complex.

The point of this discussion about celestial mechanics is the we know the Newtonian laws of motion, but even these relatively simple laws generate phenomena that can defeat prediction. Analysis under the more complex Einsteinian laws of motion become even more difficult. The Black-Scholes partial differential equation, which we referred to above, can be seen as the analogue of the computation of the geodesic in cosmology. Once we have rejected the notion that the economy seeks equilibrium, then we are obliged to accept the real possibility of singularity and chaos in its behavior. As a result of his research in celestial mechanics, Poincare (1908) was led to the realization that any deterministic system could, in principle, be chaotic. As he wrote:

> If we knew exactly the laws of nature and the situation of the universe at the initial moment, we could predict exactly the situation of that same universe at a succeeding moment. but even if it were the case that the natural laws had no longer any secret for us, we could still only know the initial situation approximately. If that enabled us to predict the succeeding situation with the same approximation, that is all we require, and we should say that the phenomenon had been predicted, that it is governed by laws. But it is not always so; it may happen that small differences in the initial conditions produce very great ones in the final phenomena. A small error in the former will produce an enormous error in the latter. Prediction becomes impossible, and we have the fortuitous phenomenon.[6]

We now turn to the possibility of chaos in climate, and its influence on humankind.

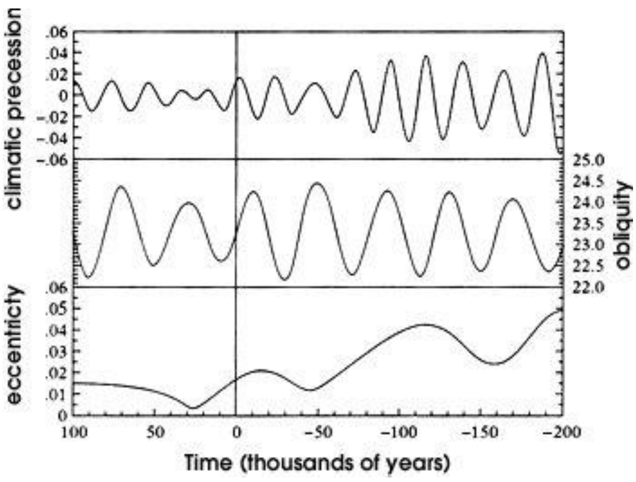
4 *The Holocene*

The impact of large asteroids may have a dramatic effect on the biosphere of the earth, and these have been suggested as a possible cause of mass extinction. The onset and behavior of the ice ages over the last 100,000 years is very possibly chaotic, and it is likely that there is a relationship between these violent climatic variations and the recent rapid evolution of human intelligence (Calvin, 1991, Fagan, 2010). More generally, evolution itself is often perceived as a gradient dynamical process, leading to increasing complexity. However, Gould has argued over a number of years that evolution is far from gradient-like: increasing complexity coexists with simple forms of life, and past life has exhibited an astonishing variety.

Evolution itself appears to proceed at a very uneven rate, and Gould used the term "punctuated equilibrium" to refer to these singularities that differentiated domains of evolutionary volatility.[69] By anology with the use of the term *singularity* in celestial mechanics, I shall use it to refer to a "gate" or portal between qualitatively different dynamical systems. To illustrate, although topology asserts that there are singularities in a flow on the geosphere, as described above, it is necessary to use chaos theory in an attempt to understand the creation of a hurricane or an earthquake. The same point holds more generally for any attempt to model the qualitative changes that can occur in weather and climate.[70]

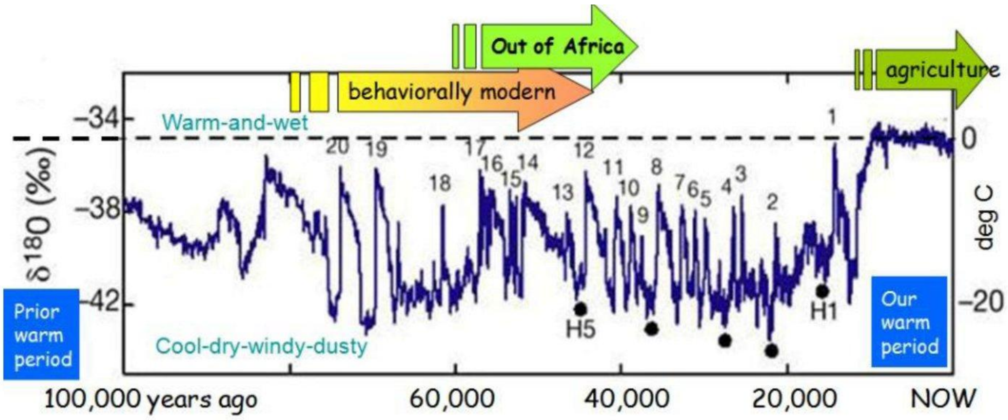
One of the concerns about climate is that it may exhibit complex singularities. For example, the spatially periodic, oceanic flow of water, including the Gulf stream, has switched off, and then on again, in the past. These switches can be interpreted as singularities that have caused catastrophic changes in climate, and have, in turn, been caused by subtle changes in the underlying periodicities of the system. Since the end of the last ice age, during the period of the *holocene* of the last twelve thousand years, humankind has benefited from a structurally stable and mild climate domain, conducive to agriculture. Figure 3 shows average global temperature for the last 100K years, taken from Greenland ice cores. There is a singularity about 90K years ago, then a long chaotic period of about 80K years, and then a singularity about 12K years ago, leading to the holocene. Just before the holocene, there was a brief ice age, the "Younger Dryas," lasting approximately 1,300 years, from about 12,800 to 11,500 years ago. Broecker describes how the global climate "flickered" in a particularly chaotic fashion, over periods of between 5 and 45 years, just before passing through the singularity that heralded the holocene.[71] The dynamical system of the "biosphere", the whole system of life on Earth, is so interwined with that of the geosphere that computer-based quantitative analysis can only hint at the connections.[72]

Figure 3: Climate 100K BCE to now: chaos from 80K BCE to 10KBCE (Source: Global-Fever.org).



As we noted above, the earth's climate is affected by periodicities in the rotation of the Earth, as well as by the oscillatory behavior of the Solar irradiation (with an eleven year sunspot cycle). The celestial cycles are associated with the eccentricity of the orbit (with a period of order 95,000 years), the Earth's tilt or obliquity (with a period of about 41,000 years), and precession (of period about 26,000 years).[73] As Figure 4 illustrates these oscillationa are periodic and non-chaotic in themselves. However, as the work of Broecker and many others illustrates, their interactive effect on the Earth can induce transformations in climatic behavior that are chaotic over certain domains. Clearly the oscillatory celestial events, as illustrated in Figure 4, cannot, by themselves, account for the climatic behavior presented in Figure 2. In other words there may be two entirely different domains, a stable one like the holocene, and a chaotoc one, just before the holocene. In addition, exotic celestial events, like the collision with the asteroid, 65 million years ago, can induce major singularities and flip the biosphere into a different domain.[74] It is increasingly understood that the dynamics of the geosphere and biosphere interact through multiple feedback mechanisms. The melting of the ice caps resulting from a temperature change modifies their albedo, reflecting less heat energy, further raising world temperature, increasing oceanic volume, affecting forest evapotransportation as well as the global algae populations. The oceanic conveyor (and thus the Gulf Stream) can, and has, shut down. Methane can be liberated from deep ocean domains and from land, due to the decay of pemafrost.

Figure 4: Oscillations in precession, obliquity and eccentricity



Cloud formations may change as the weather system is transformed, and intense families of hurricanes spawned in the oceans. All these possible changes are deeply chaotic because they involve fundamental transformations in the nature of the balance between our civilization, the oceans, the land and the atmosphere. It is now well established that even relatively small changes in climate, over the last few thousand years, have had profound effects on our civilization, the *anthrosphere*.[75] Over the longer run of 100K years, our rapid evolution was the consequence of the chaotic climate prior to the holocene. The population growth from about 6 million, at 12K years ago to over 6 billion now is due, of course, to the spread of agriculture, but this was possible only because of a relatively stable climate.[76] We have only recently realized that population growth and economic activity have induced links from the anthrosphere *to* the biosphere and geosphere. In fact it is now believed that these effects have been present since the beginning of agriculture about 12K years ago, but the relative stability of the Holocene obscured this connection. It is precisely because small changes can induce sin- gularities that we now fear that human activity may be be sufficient to “force” the biosphere through a new singularity into a “hot zone, ” with a qualitatively different dynamical system.Metaphorically speaking, it would be like passing through a black hole into a totally different universe. The point is that the portal to the singularity would be chaotic. Indeed it has been suggested that our behavior may have brought the Holocene to an end, and we should note this by calling the new world the *Anthropocene*.

5 The Anthropocene

While GE may assert the existence of a general full-employment equilibrium, recent events seem to support the thesis presented here that economic behavior in our sophisticated markets may also induce complex or chaotic singularities in the flow of the economy. Indeed, it has dawned on us that these lurches from one crisis to another make it even more difficult to see how to plan for the future. If the onset of climate change induces the kind of chaos that occurred prior to the holocene, then we can expect economic hurricanes in the future. More to the point, well before we hit a climatic singularity, there may occur totally unexpected eventualities, such as Malthusian crashes, or Katrina events. For this reason, the future we face exhibits the kind of fundamental uncertainty that Keynes emphasized. It can be argued that the degree of uncertainty is so pronounced that we should plan for the future with extreme risk aversion.[77]

The National Academy of Sciences has recently published three reports on climate change and has asserted that A strong, credible body of scientific evidence shows that climate change is occurring, is caused largely by human activities, and poses significant risks for a broad range of human and natural systems.[78] However, the global downturn has led to severe disagreement between nations about how to attempt to deal with climate change at the international level. It was only because of pressure from President Obama that the Copenhagen Accord was agreed to, in December 2009, by the United States together with four key emerging economies - China, Brazil, India and South Africa. The relative economic stability of the 1990’s may, in the future, seem like an economic holocene, maintained by the dominance of the United States. This period seems to have come to an end, and it may well be that without such a hegemon, political instability will be exacerbated.[79] To preserve democracy, Keynes believed that government intervention to control market volatility was the answer, coupled with the preservation of the free market in commodities.[80] But as ever, to constrain or regulate a market, it is necessary to control assets sufficient to do the job, and the scale of these required assets depends on the size of the market and its inherent volatility.

The decades long growth and globalization of the international economy means that the assets used for control must be of the order of many trillions of dollars. The United States does not control sufficient assets. Schumpeter was sanguine about the consequences of market volatility. As he wrote This process of Creative Destruction is the essential fact about capitalism. It is what capitalism consists in and what every capitalist concern has got to live in..It must be seen in its role in the perennial gale of creative destruction..[81] If the volatility of the market is no more than a cyclic phenomenon, then we can agree with Schumpeter. Minsky, a student of Schumpeter, was much less sanguine. While accepting Schumpeter's view of the transformative role of technology, he feared the consequences of financial chaos.[82] In fact, it seems that the globalization and transformation of the world economy in the last few decades has created much more complex feedback mechanisms in the world political economy. It is this increased complexity in the international system that has made it more susceptible to belief cascades, and to the possibility of singularity.[83]

In a sense, our own hubris has brought this on ourselves. If we can no longer trust the market t behave in a fairly stable fashion, then we have to understand it better, in order to regulate it, or partially control it. At the same time however, we also face the possibility of climatic chaos, generated by the additional complexity of our own behavior affecting an already subtle dynamical system. We face a quandary of uncertainty, since we neither understand the Anthropogenic that we have created, nor the way in which it is affected by the biosphere and climate. This global quandary creates many localized quandaries about how to proceed in the short and medium term.[84] Although President Obama seems aware of the quandary, he faces a divided Congress, and a Senate, conservative in its policy preferences, because of its use of a supermajoritarian voting rule. It would seem that facing the quandary of the future will depend on our ability to better understand the global economy that we have created. A high degree of risk aversion would seem like a good first step. But to do this requires concerted and cooperative action by all the major powers, including at a minimum, the United States, the European Union and China. An appreciation of the failure of our theories about economic equilibrium and an acknowledgement of fundamental uncertainty and chaos may help us proceed with caution.

N o t e s

- This article is based on work supported by NSF grant 0715929. It is dedicated to the memory of Hyman Minsky, who was my colleague for many years at Washington University in Saint Louis.
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- Weber (1904) speculated that there was a connection between the values of Protestantism and Capitalism. It may be that there are connections between the preference for scientific explanation and protestant belief about the relationship between God and humankind.
- See Feingold (2004).
- Hawking (1988) writes of being able to read the "Mind of God."
- See for example, Landes (1998) and Warsh (2006).
- For Hobbes, see Rogow (1986). For Descartes, see Gaukroger (1995). For Spinoza and
- Liebnitz see Stewart (2006) and Goldstein (2006).
- It is of interest that the English word "soul" derives from Old English *s wol* (first used
- in the 8th century poem, *Beowulf*
- Hawking and Mlodinow (2010) assert that God did not create the Universe, perhaps
- implying that the soul does not exist. However they do say that they understand Isaac
- Newton's belief that God did create and conserve order in the universe. See other books
- by Dawkins (2008) and Hitchens (2007) on the same theme, as well as Wright (2009) on the
- evolution of the notion of God.
- See Lieven (2002) for a brief history of these empires and Overy (2009) for the fears about
- collapse in the interwar years in Britain.
- A recent Gallup poll found that 70% of Americans regarded religion is an important part
- of their daily lives, compared with 27% of British.
- See also Wright (2009).
- Strong reciprocity means the punishment of those who do not cooperate.
- Indeed, White et al.(2009) present evidence of a high degree of cooperation among a
- very early hominid, *Ardipithecus ramidus*, dating back about 4MYBP (million years before
- the present). The evidence includes anatomical data which allows for inferences about the

- behavioral characteristics of these early hominids.
- Gintis cites the work of Robson and Kaplan (2003) who use an economic model to estimate
- the correlation between brain size and life expectancy (a measure of efficiencey). In this
- context, the increase in brain size is driven by the requirement to solve complex cooperative
- games against nature.
- “Culture” can be thought of as the social context in which these norms are maintained.
- See Cavalli-Sforza and Feldman, 1981; Wilson (1978); Lumsden and Wilson (1981). .
- Gigerenzer 2007; Ridley, 1998; Wright 1994, 2000; Boyd and Richerson, 2005; Jablonka
- and Lamb, 2006.
- Gazzaniga, 2008.
- Bloom, 2004, 2010.
- De Waal, 1996, 2006.
- This is derived from the work of Chomsky (1972) and Pinker (1997, 1999),
- See also Bowles et al. (2003), Bowles (2006), Choi and Bowles (2007) and Pinker and
- Bloom (1990) who present models of the co-evolution of language, institutions and coopera-
- tion.
- See Henrich et al. (2004, 2005), which reports on experiments in fifteen “small-scale
- societies,” using the game theoretic tools of the “prisoners’ dilemma,” the “ultimatum game,”
- etc. See also the review by Samuelson (2005).
- Price’s work was used by Maynard Smith (1972, 1982) to develop the idea of an evolution-
- ary stable strategy, and by Hamilton 1970) in a model of spite. See Frank (1995), Hamilton
- (1995) and Harman (2010) for discussion of Price’s work.
- See also Binmore (2009).
- Wrangham (2010), for example, argues that the use of fire for cooking enhanced sharing
- norms.
- Societies with free markets and extended franchise are termed open access societies by
- North et al. (2009).
- Mokyr (2010) charts the changes in belief that occurred in Britain in the period of in-
- dustrialization, 1700-1850. David Kennedy (2001) gives a historical account of the political
- changes that occurred in the U.S. in the period from 1900 to 1945.
- Reich (2007, 2010).
- Westen (2007) comments on the influence of moral values on political choice.
- See Dawkins (1976) and later work by Dennett (1995) and Blackmore (2000).
- Dennett (2003).
- Indeed, much of the literature cited above can be seen as part of an extensive effort to construct a formal theory of moral values and beliefs based on the mathematical model of
- game theory.
- See Ferguson (2001, 2002, 2004), Zakaria (2003), James (2006), Murphy (2007), and
- Bacevich (2008, 2010)
- The Stockholm International Peace Research Institute estimated that the US 2009 military
- budget was $663 billion about 4.3% of GDP. An estimate for the Department of Defense budget
- for fiscal year 2010 is $685 billion. This expenditure has risen since 1999 when it was about
- 3%. However, other defense spending on Iraq and Afghanistan has brought the total for 2010
- to about $ 1 trillion, about 7.5% of GDP. See the discussion in Johnson (2004) on militarism.
- See Jacques (2010) on the rise of China as a rival, and Shapiro (2008) on the changes in
- the balance of power as a result of globalization.
- It seems that full democracy is far more difficult to build than was originally believed.
- The economic crisis has also led many to infer that the economic model underlying capitalism
- is completely wrong.
- The comments by von Hayek and Greenspan are cited in Ramo (2009).
- See also the argument in Chichilnisky (1996).
- Total US emissions are about 5.6 million metric tons/ annum. One US gallon of gasoline
- costs $2.70 and emits about 20lb of CO_2 when combusted. If the USA imposed a tax of $40 on
- every quantity of gasoline that would emit one metric tonne of CO_2 during combustion, the
- carbon tax on this gallon of gasoline would be 22 cents, an 8% increase. An average motorist
- uses about 400 gallons/annum and so emits less than 4 tons of CO_2/ annum.
- In fact, Binmore (2009) argues that decision making in “large worlds” faces epistemic
- problems resulting from the G del-Turing Theorem.
- See Mlodinow (2008) for a discussion of chaos and randomness and Thuan (2000) for a
- discussion of the applicability of the idea of chaos in scientific revolutions.

- See Prigogine (1997) for a philosophical discussion of the general ideas underlying this theory, and Beinhocker (2006) for a wide ranging application of some of these ideas to eco- nomics.
- Wrangham (2009)
- Cann et al (1987). We use KYBP to mean thousand years before the present.
- Such a catastrophic event would cause a bottleneck in the development of *H.sapiens*, and
- may have induced a sudden and very rapid transformation in the evolutionary path.
- See North et al. (2009).
- See Schofield (2010).
- For Britain, Maddison (2007) estimates that GDP/capita grew from $1250 in 1700 to
- $1750 in 1820, measured in 1990 international Geary Khanis (GK) dollars. However, estimates
- of the real wage of building workers in 1700 and 1820 by Clark (2007) are identical. This implies
- inequality increased. The estimates by Rourke and Williamson (1999) suggest inequality in
- the US only started to increase after 1890. See also Schofield (2008).
- These are the estimates by Maddison (2007), measured in 1990 international Geary Khanis
- dollars.
- Reich (2007) notes that the richest 1% received about 20% of income in 1927 but only
- 10% in 1970.
- See Krugman (2009), for a recent argument that the assumptions of economic theory are
- unrealistic.
- See also Stiglitz, (2010) for a recent discussion of the failure of these protocols.
- Galileo Galilei ([1610],1992);[1632], 1967), [1638], 1974); Newton, [1687],1995)
- See Galison (2003).
- See O'Shea, (2007). Perlman recently won a million dollar Millenium prize for his theorem
- from the Clay Mathematics Institute. For an outline of Perlman's result see Morgan and Tian
- (2007).
- See Vladimir Arnol'd, (1963) and Message (1984)..
- Had the solar system been chaotic, then life would not have evolved on Earth.
- Don Saari and Zhihong Xia, 1985. "The Existence of Oscilatory and Superhyperbolic
- Motion in Newtonian systems," *Journal of Differential Equations* 82 (1989) : 342-355.
- See the discussion of space-time singularities, such as black holes, in Hawking and Ellis
- 1973) and in Penrose (2003).
- Henri Poincar ([1908], 2007). Poincar 's argument even holds in the very long run for
- the solar system. Current simulation can estimate all planetary orbits forwards and back for
- about 5 million years, the *horizon of predictability*.
- See .Gould, 1989, and Eldridge and Gould, 1972.
- Sometimes climate does hit an equilibrium, when the planet becomes an ice ball. It only
- escapes such an equilibrium because of tectonic activity. See Macdougall, 2004.
- See Broecker (1997, 2010). There was also a very brief ice age about 8,200 years before
- the present.
- See Edwards (2010) for an overview of current computer models of climate.
- The changes in eccentricity are due to the perturbations on Earth's orbits induced by the
- other planets. See Hays, Imbrie, and Shackleton (1976) for a discussion of the work of Milutin
- Milankovitch who hypothesised that these "celestial" oscillations affected climate. See also
- Hansen (2009) for the resulting correlated changes in temperature, CO_2 concentration and
- sea-levels over the last 400 thousand years induced by these celestial oscillations..
- See Luis Alvarez et al., (1980). See also Benton (2003) for the much more severe Permian
- mass extinction about 250 million years ago. It is believed that extensive volcanic activity
- released enormous amounts of CO_2 and chlorine, causing a runaway greenhouse effect . The
- effect was further stimulated by the melting of frozen gas hydrates, and led to a global 6
- degree Celsius rise in temperature. About 90% of all species became extinct.
- See Fagan, 1999, 2008) and Diamond (2005) on the Medieval Warm (800CE to 1300CE)
- and the Little Ice Age (1300 to 1850CE).
- World population growth rate increased from about 0.07% 12K years ago to about 0.08%
- 2K years ago to about 0.4% in 1650. The "Malthusian barrier" was broken about 1950 with
- a growth rate of about 1.6%. See Kremer, (1993).
- See Stern (2007) and Rockstrom et al.(2009). This uncertainty stems essentially from the
- very limited horizon of predictability that we can reasonably impose on the interaction of the
- anthrosphere and climate.
- National Academy of Sciences reports, "Limiting the Magnitude of Future Climate
- Change", "Adapting to the Impacts of Climate Change", "Advancing the Science of Climate

- Change". See http://dels-old.nas.edu/climatechange.
- See Kennedy (1987). As an illustration, the trade deficit of the United States with China
- increased from $103 billion in 2002 to $268 billion in 2008, though it dropped to $227 billion
- in 2009. China now holds $2.4 trillion in foreign currency reserves. On the rise of China as a
- rival, see Jacques (2010).
- As did Hayek, Keynes believed the free market in commodities was conducive to both
- efficiency and liberty.
- Schumpeter (1942).
- Kurzwell (2006) welcomes the singularity that he believes will be generated by the com-
- ing scientific and computer-based changes. The application of sophisticated computer and
- mathematical tools in finance, and the disaster that was caused is described in Patterson
- (2010).
- Mathematics will be essential to the task of modeling these systems.As noted above,
- however, the attempt to model risk through computer models during the economic holocene
- contributed to our current situation. I believe the mathematical models of finance brought
- about the current economic disaster because they failed to incorporate the complexity of belief
- cascades.
- Ferguson (2010) suggests that the American Empire, like earlier ones, may collapse in a
- chaotic fashion. The total US federal debt is a concern. It increased from $5 trillion in 1992
- to $7 trillion (about 70% of GDP) in 2000 to $17 trillion (about 116% of GDP) in 2010

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