Chaos Theory and Metaphysical (In) Determinism

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The Enlightenment was filled with heady ideas about the predictive ability of science. The philosophy of scientific materialism - that all things are composed of matter and can thus be fully understood, at least in principle, by the scientific method – led many to believe that the evolution of the cosmos is completely determined by natural law, and the initial state of that cosmos. As this belief in determinism is itself outside of the realm of the physical, it is sometimes termed metaphysical determinism. The philosophy was given its most succinct – and bold – expression by Pierre Simon de Laplace, in 1814:

> "We may regard the present state of the universe as the effect of its past and the cause of its future. An intellect which at a certain moment would know all forces that animate nature, and all positions of all items of which nature is composed, if this intellect were also vast enough to submit these data to analysis, it would embrace in a single formula the movements of the greatest bodies of the universe and those of the tiniest atom. For such an intellect nothing would be uncertain. The future, just like the past, would be present before its eyes."

The hypothesis of determinism was undermined by science itself, as it was discovered that many physical systems are considerably less orderly than some had hoped. Alongside quantum mechanics, chaos theory - the mathematics of dynamical systems – played a large role in the re-evaluation of scientific determinism. In 1986, looking back over the previous few decades, Professor James Lighthill, then president of the International Union of Theoretical and Applied Mechanics, wrote

> "We collectively wish to apologize for having misled the general educated public by spreading ideas about the determinism of systems satisfying Newton's laws of motion that, after 1960, were proved to be incorrect. Modern theories of dynamical systems, have clearly demonstrated the unexpected fact that systems governed by the equations of Newtonian dynamics do not necessarily exhibit the `predictability' property."

Yet not all scientists agree, and the debate between determinism and indeterminism is still unresolved.

Many Christians are unsettled by the theory of metaphysical determinism, for it seems to take God 'out of the equation.' Understandably, then many have latched onto Chaos Theory for its seeming ability to dismiss the materialistic philosophy, and to demonstrate the possibility of metaphysical divine interaction. The Christian community looks to those among us who are both theologians and mathematicians to ensure that the issues are understood clearly.

This paper will begin by introducing the issues that arise for the Christian mathematician and scientist: What is at stake in this debate? It will then briefly review chaos theory, by means of two examples. It will then introduce the metaphysical interpretations given to chaos theory by three different scientist-theologians. Sjoerd Bonting's position is that chaos definitely demonstrates an indeterministic world, a position which I call strong indeterminism. Robert Russell argues that chaos strengthens the argument for determinism, while also limiting that argument from becoming any stronger. I characterize his position as weak determinism. John Polkinghorne argues for weak indeterminism, suggesting that, while chaos theory itself cannot answer the question definitively, it points in the direction of metaphysical indeterminism. Polkinghorne's work in this field has been taken up by proponents of open theism, theologians who argue that the biblical record does not demonstrate exhaustive, but rather partial, divine foreknowledge. The paper will conclude with a brief introduction to open theists, and analyze their use of chaos theory to support their theological claims.

1. Determinism or Indeterminism: What's at stake?

What, then, is at stake, for Christians, in the debate between metaphysical determinism and indeterminism? Most broadly, the philosophical choice is between deism and theism. A deist believes in a deterministic creation, and in a God who, beyond the act of creation itself, is essentially uninvolved in the cosmos. The most common metaphor for this kind of God is the clockmaker who made the clock, wound it up, and forever after leaves it alone to run as it will. Most Christians, however, are theists, who believe that God is not only the Creator, but is also active – and interactive – in creation. But if God is to be involved on a day-to-day basis, creation must be indeterministic and free. This does not speak to the question of divine foreknowledge, but simply insists that God does in fact respond to creation in real time.

Several theological issues depend, for their discussion, on one's position on metaphysical (in)determinism. The level of freedom one imparts to the cosmos will dictate at least some aspects of one's position on the following:

- Divine action – Does God act in the world? How does God act?
- Miracles – Must God break the laws of physics to intervene, or can God act within the natural laws of the universe?
- Prayer – Does it matter? What is the effect of prayer, and perhaps especially of petitionary prayer?
- Problem of evil – If God is all-powerful and good, then why is there evil in the world? Theodicy – How can God's power, goodness and righteousness be defended in the face of evil in the world?
- Free will vs predestination – Is this an ontological question or a question of divine epistemology? If the world is deterministic, then predestination is in the category of existence (ontology). If the world is indeterministic, then free will is ontological, and predestination is epistemological.

In each of these cases, the theologizing is necessarily intertwined with the question of metaphysical determinism.

Regarding the question of divine foreknowledge, Christian beliefs lie along a spectrum. In Calvinism, God's foreknowledge is termed 'exhaustive.' Everything is known by God before it happens, even the free decisions that we make. All is pre-ordained. Arminians hold that God's foreknowledge is 'subsequent.' Free decisions are not necessarily pre-ordained, but since God exists outside of time, so God sees all things as "having happened". Open theists believe in partial divine foreknowledge. There is a component of time to God's existence. God knows some things in advance – eg Messianic prophecies, the existence of the Church, the broad outlines of eschatology. But God gives humans, and for that matter all of creation, genuine free will – eg.

Conditional prophecies, God "changing his mind," God acting surprised. Open theism is a relatively new expression, held by evangelical theologians Gregory Boyd, Clark Pinnock, John Sanders, and others. Finally, process theists believe in no divine foreknowledge. In the expression of the famed philosopher-mathematician Alfred North Whitehead, and the theologian Pierre Teilhard de Chardin, God is part of creation, and evolves along with it. Process defines God's existence. The cosmos is converging toward the Christ, a unified consciousness which Chardin labelled the "Omega Point." We must note that these are four positions along a spectrum of beliefs, and that one may call oneself a process theist, for example, without holding to the extreme views of Whitehead and de Chardin. However, it is possible to characterize this spectrum of beliefs on a scale of determinism, with Calvinism leaning most strongly toward determinism, and process theism as strongly indeterministic.

2. Chaos Theory

Since its popularization in the 1960s, many philosophers, theologians and scientists have suggested that the mathematics of dynamical systems – 'chaos theory' in the language of the layperson – speaks directly to the question of determinism. We shall review the relevant portions of chaos theory by means of two, by now classical, examples, the logistic map and the Lorenz equations.

Example 1: The Logistic Map

The logistic model for population growth is the ordinary differential equation

$$\frac{dN}{dt} = pN\left(1 - \frac{N}{C}\right), \; N(0) = N_0,$$

where $N(t)$ is the population size at time t, $p>0$ is the reproductive rate of the population in the absence of environmental factors (the simplest model of this is the birth rate minus the death rate), and C is the carrying capacity of the environment, i.e. the population which can be sustained by the environment's resources. This model has proven to be quite successful in predicting the fluctuations of insect colonies, such as locusts and moths. The model is based on the theory that very small populations will have a growth rate nearly equal to the reproductive rate, that populations near to the carrying capacity will have a much slower growth rate, and that populations above the carrying capacity will have a negative growth rate.

The discrete version of the logistic equation is

$$N_{k+1} = N_k + pN_k\left(1 - \frac{N_k}{C}\right),$$

where the time period between populations N_k and N_{k+1} is constant. After reparametrization and scaling, it can be written in the classical form,

$$x_{k+1} = rx_k(1 - x_k),$$

which is known as the logistic map. The equation is typically explained in terms of a hypothetical moth colony, where x_k is the ratio of the current population to the carrying capacity (so that an extinct population is represented by $x_k = 0$, and a population that is perfectly sustainable by the environment has $x_k = 1$), where x_{k+1} represents the population at the next time period (for example, one year later), and r, called the fecundity, represents the reproductive ability of the moth colony.

Population trajectories for four different fecundities are shown in Figure 1. In all cases, $x_0 = 0.3$, which represents an initial moth colony population of 30% of the environment's capacity for sustainability. The horizontal axes represent time, specifically k time periods after the initial measurement. The vertical axes represent the scaled population size.

Each of the four fecundities represented in Figure 1 result in a different characteristic trajectory. When $r = 0.9$, the population asymptotically approaches $x = 0$, representing eventual extinction. When $r = 2.8$, the population asymptotically approaches $x = 0.64$, representing an eventually stable population of 64% of the environment's capacity. When $r = 3.2$, the population asymptotically approaches two alternating but stable states, $x = 0.51$ and $x = 0.80$, representing a population that eventually oscillates, year-by-year for example, between two distinct sizes. When $r = 3.52$, the population eventually oscillates between the states $x = 0.51$, 0.88, 0.37, and 0.82, in a four-year cycle. This pattern of cyclic oscillation between different stable population sizes has been observed in naturally occurring populations such as moth colonies.

Observing that each fecundity in Figure 1 has a different, but stable, eventual state, one wonders about the relationship between the fecundity r and these asymptotic states The bifurcation diagram in Figure 2 represents this relationship. For each value of r along the horizontal axis, each asymptotic population state is plotted vertically. For all fecundities less than $r = 1$, the population eventually becomes extinct, so the bifurcation diagram has a straight horizontal line (not shown) at $x = 0$, from $r = 0$ to $r = 1$. From $r = 1$ to $r = 3$, the population asymptotically approaches one single, stable population size, which increases as r increases. The trajectory for $r = 2.8$ in Figure 1, which asymptotically approaches $x = 0.64$, is thus represented as the point (2.8, 0.64) in Figure 2. Similarly, the trajectory of $r = 3.2$, which eventually oscillates between two stable states, is represented as the two points (3.2, 0.51) and (3.2 0.8). The four points (3.52, 0.37), (3.52, 0.51), (3.52, 0.82), and (3.52, 0.88) represent the four eventual states for $r = 3.52$. Note that the bifurcation diagram indicates nothing about the order in which these states occur, only that the population eventually oscillates between those four states.

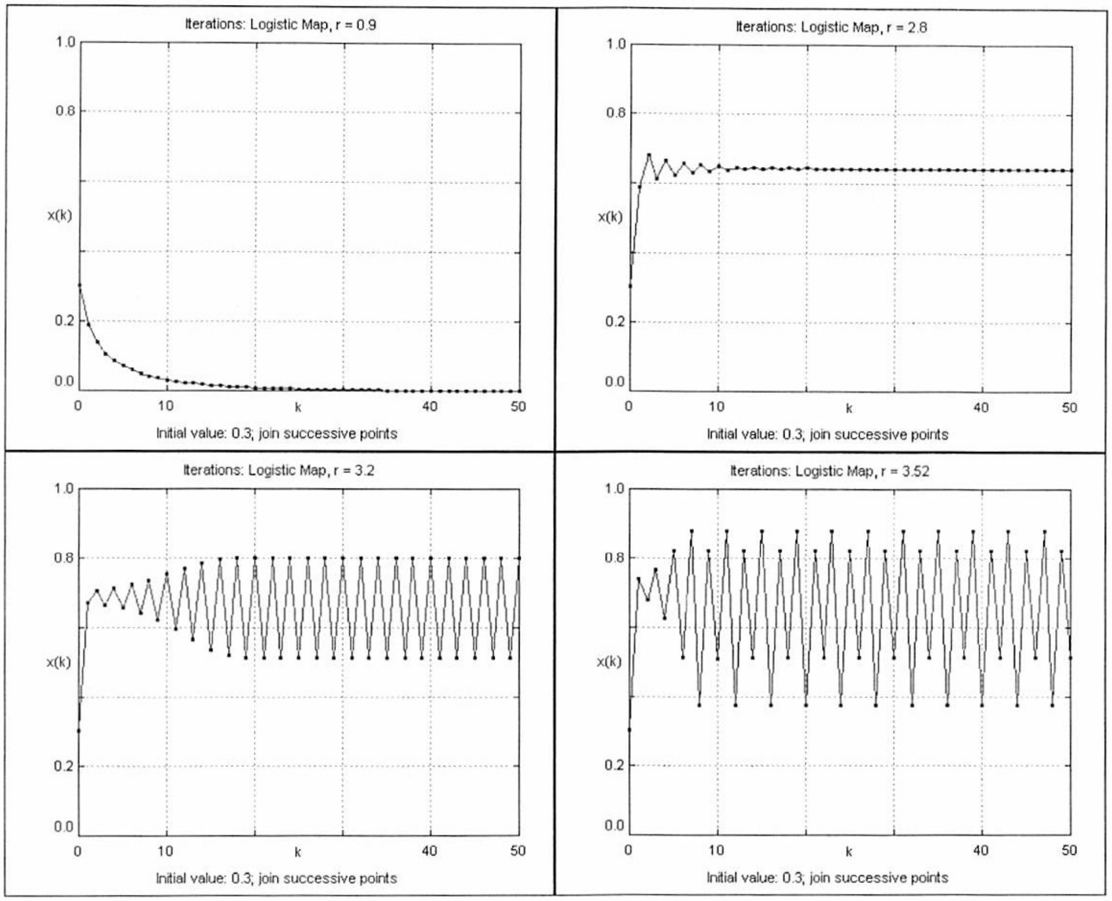

Figure 1. Sample trajectories of the logistic map.

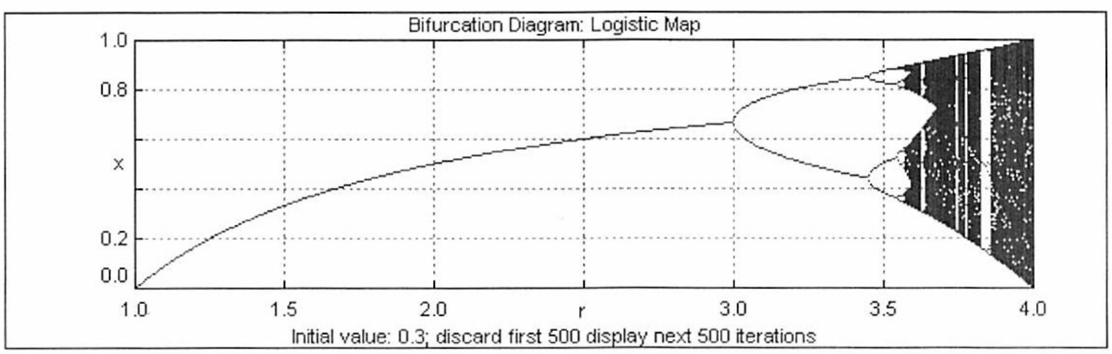

Figure 2. Bifurcation diagram for the logistic map.

The bifurcation diagram is so-called because of the way the eventual states bifurcate at certain values of r. For example, for $r < 3$, the population eventually converges to one stable size, but for $r > 3$, the population begins to oscillate – first between two different states, then after about $r = 3.45$ between four states, then after about $r = 3.544$ between eight states, etc. These initial bifurcations are known as period-doubling bifurcations, and there are infinitely many of them. Notice that the change in r between these period-doubling bifurcations decreases – apparently geometrically – as r increases. In fact, the ratio between these bifurcations is approximately 4.669, which is known as Feigenbaum's number.

Because of this geometrically diminishing distance between bifurcations, the infinite number of period-doublings occurs within a finite range of r values, approximately $3 < r < 3.56994$. Beginning at approximately $r = 3.56994$, the logistic map enters the so-called chaotic region, in which there is no longer any asymptotically stable behavior whatsoever. In fact, there is no pattern to the population trajectory, except that for large values of time the population sizes all lie within the darkened sections of the bifurcation diagram. Within those bounds, the trajectory cannot be distinguished from complete randomness, with no one population size ever recurring as time moves on.

This chaotic region is crucial to the arguments about metaphysical determinism. For this range of r values, if two populations have the same fecundity but two slightly different initial values, the two population trajectories will end up looking radically different. This situation, known as sensitivity to initial conditions, is a characteristic of all chaotic maps. Here it is key to notice that, while the logistic map maps real numbers onto real numbers, the trajectories are always calculated with finite precision. Sensitivity to initial conditions means that after some time, the computed, finite-precision trajectory, is in fact completely different from the actual, real-valued, infinite-precision trajectory. In fact, as long as we are restricted to finite-precision calculations, it is impossible to know any actual trajectory in this chaotic region. It is then a matter of philosophical debate whether this limitation is merely epistemological, or might in fact be ontological, a distinction which will be discussed in detail below.

Remarkably, this chaotic region is limited. At $r = 3.83$, order emerges out of the chaos, as the trajectories become stable once again, oscillating now between one of three possible states. As r increases, this period-three region itself undergoes an infinite period-doubling bifurcation, leading to yet another chaotic region. This pattern is repeated at many scales, for many different periodic regions.

Finally, we note that despite the radical disorder of certain segments of the logistic map, there are also some overall characteristics of order. The random behavior occurs within finite bounds. The Feigenbaum number determines the dimensions of the period-doubling. The period-doubling cascade is a fractal, the pattern repeated at every magnification level. The logistic map thus has characteristics both of order and disorder – metaphors at least for the theological dialectic between the faithfulness of God and the freedom of creation.

Example 2: The Lorenz Equations

The Lorenz equations model the weather system in our atmosphere. Air near the earth is heated and rises, where it is cooled in the atmosphere and returns to the earth. The convection cells that develop can be described in terms of the convective flow and the temperature distributions, in a dynamiical system of three differential equations

$$\begin{cases} \dfrac{dx}{dt} = \sigma(y-x) \\ \dfrac{dy}{dt} = \rho x - y - xz, \\ \dfrac{dz}{dt} = xy - \beta z \end{cases}$$

where $x(t)$ represents the convective flow, $y(t)$ the horizontal temperature distribution, $z(t)$ the vertical temperature distribution, and where σ, ρ and β are positive, real-valued parameters which depend on the characteristics of the atmosphere.

Interest in the chaotic aspects of dynamical systems took off in the 1960s when Lorenz discovered accidentally that for certain parameters, this set of equations is sensitive to initial conditions. In 1960, Lorenz was using a vacuum-tube computer, calculating at 60 multiplications per second (!), to solve numerically the equations with parameters $\sigma = 10$, $\rho = 28$, $\beta = 8/3$. To re-examine some of the solutions, he restarted one particular solution run in the middle. Though the computer was calculating with 6-decimal-place accuracy, it only reported the first three, so Lorenz was effectively rounding the initial values to 10^{-3}. He was shocked to discover that this tiny disparity in initial conditions yielded a solution that initially followed the same trajectory, but soon diverged into a startlingly different solution. One can find many examples of this online, and as it is easier to observe the sensitivity effect with color and motion, the reader is invited to Google "Lorenz equations sensitivity." The result demonstrates the difficulties inherent in computer weather prediction. For certain parameter sets, slightly different initial states will lead to radically different overall trajectories. Once again, then, finite precision computation means that we can never know the actual trajectories in these chaotic regions.

Yet once again there is order within the chaos. For the same parameter set, even though two trajectories may be radically different, they will both lie on the same topological set. For example, Figure 3 shows the three-dimensional trajectories, using Lorenz's parameters given above, and initial value sets differing by 0.001. Both solutions lie on the three-dimensional surface known as a strange attractor – in this case a twisted butterfly. In fact, for this set of parameters, the solution for any set of initial conditions will eventually lie along the Lorenz attractor.

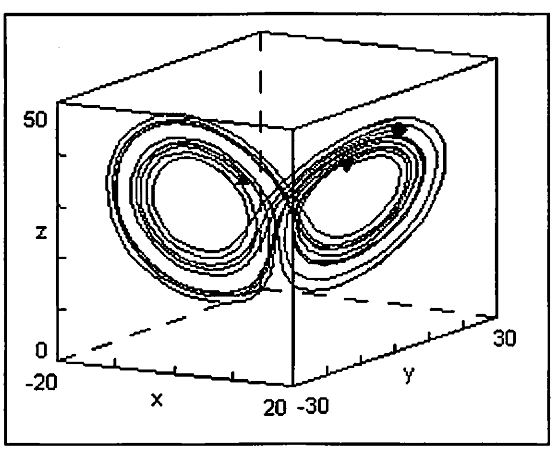

Figure 3. The Lorenz attractor, for $\sigma = 10$, $\rho = 28$, $\beta = 8/3$.

To review, then, some of the properties of chaotic dynamical systems include sensitivity to initial conditions, yet also attractors, fractals, Feigenbaum dimensions. The systems arise from computable equations, and are thus completely deterministic yet because of the infinite complexity and sensitivity we know that we cannot calculate solutions even approximately. Within chaos theory, then, we have both disorder on a massive scale, and order within the disorder. Solutions can be known in part, yet be practically utterly unknowable. James Gleick, author of *Chaos: Making a New Science* (Penguin Books, 1987), has described this phenomena as "stable chaos," and "deterministic disorder," and "regular irregularity."

3. Metaphysical Interpretations of Chaos Theory:

Many scientist-theologians have become enamored with chaos theory, because of its ability to model both orderly and apparently random phenomena, and because it has effectively removed any hope of predictability for certain systems that obey Newtonian mechanics. In particular, it has been used to address questions of metaphysical determinism, and, directly or indirectly, the theological questions raised in section 1 above. The three positions laid out below are characterized based on the theologian's opinion about how strongly Chaos Theory supports either determinism or indeterminism.

3a. Sjoerd Bonting: Strong Indeterminism

Sjoerd Bonting has a PhD in biochemistry, and is an ordained Anglican priest. He is the author of the book *Creation and Double Chaos: Science and Theology in Discussion* (Fortress Press, 2005) and the article "Spirit and Creation" (*Zygon,* vol. 41, no. 3, September 2006). Bonting's overall theological argument is that creation *ex nihilo* should be reformulated as creation out of *chaos*. He suggests that this makes more sense biblically, scientifically, and theologically. Biblically, in Genesis 1, where most translations have "formless void" and "create," a more accurate translation of the Hebrew would be "chaos" and "shape/ form," respectively. Scientifically, there is no theory that accounts for a pre-existent nothingness. The Big Bang requires pre-existent energy. Theologically, it is difficult to conceive of "nothing" and God coexisting. Furthermore, the problem of evil has a more rational answer if creation was an initial ordering of pre-existent chaos, some of which still exists. The coming of the Kingdom of God in Jesus is then the re-newed ordering of that element of chaos that still exists in the world.

This first "chaos" is the more popular definition, synonymous with "disorder." Bonting also refers to the mathematics of Chaos Theory. He claims that the logistic map's bifurcation diagram, for the propagation of a moth colony, shows that

> "at a bifurcation, the population size may go up or down, but it does not tell us which leg of the fork will actually be followed, the one toward higher values of x or the one toward lower values. The system has become unpredictable for us. The curve with all its bifurcations is fully 'deterministic' in the sense of observing natural law, but the moth colony can take only one of the two paths at each fork. We cannot predict which leg it will take, since there is no energy difference between them." (2005, p116-117)

He also claims that one way in which the Spirit acts in the world is by

> "influencing 'chaos events' to keep the evolving creation on track to the goal set by its Creator. It is now recognized in chaos theory that so-called nonlinear systems ... will in their development in time encounter a fork in their path ... The system can then follow one or the other leg of the fork. Because there is no energy difference between the two legs, both ways are equally likely... But this also means that a minute influence, one bit of information, can make the system follow one rather than the other leg... I suggest that this may be the opening God has reserved to correct where necessary the course of the freely evolving creation without violating any of the physical laws God laid down in the beginning... Theologically speaking, we may say that the Spirit will transmit the information necessary for the influencing of a chaos event." (2006, p722-723)

Theologian Wolfhart Pannenberg, in his article "The Problems between Science and Theology in the Course of their Modern History" (*Zygon*, vol. 41, no. 1, March, 2006), agrees:

> "I agree with the judgment of Sjoerd Bonting that, notwithstanding the deterministic character of theoretical description, 'the natural system becomes indeterministic at a bifurcation point.' I also agree with his theological defense of talking about divine 'intervention' in such a situation." (p111)

Unfortunately, Bonting's case is premised on a faulty interpretation of the bifurcation diagram, namely that

> "the computer plot describes all courses that the system may follow, while a natural system like our moth colony can obviously follow only one course at a given time." (2005, p117)

In reality, the plot describes all courses that the system DOES follow. That is, the hypothetical moth colony population converges not to one of many options, but to an <u>oscillating periodic pattern hitting ALL the options</u>. This has been described above in section 2.

3b. Robert Russell: Weak Determinism

Robert Russell has a PhD in physics, is an ordained minister in the United Church of Christ, directs the Center for Theology and the Natural Sciences in Berkeley, CA, and is co-editor of the book *Chaos and Complexity: Scientific Perspectives on Divine Action* (Vatican Observatory Foundation, 1995), in which he and Wesley J Wildman author the article "Chaos: A Mathematical Introduction with Philosophical Reflections." They write:

> "We can say without hesitation that chaos in nature gives no evidence of any metaphysical openness in nature... Put bluntly, the butterfly effect testifies to the high degree of causal connectedness in certain natural systems, and so is most naturally exploited in support of the thesis of metaphysical determinism... [T]he hypothesis of metaphysical determinism is strengthened by chaos theory because it enables the apparent randomness of even simple natural dynamical systems potentially to be brought under the umbrella of determinism. Instead of the theoretical instability of planetary orbits being a bone in the throat of apologists for determinism, for example, it is construed as an ordinary consequence of a simple deterministic system. <u>Laplace would have been delighted with chaos theory</u>." (p82, emphasis mine)

On the other hand, Chaos Theory also implies that human *knowledge* of (in)determinism is limited, because of our finiteness. Sensitivity to initial conditions means that accurate prediction, and verification of the deterministic model, would require calculation with infinite precision. Thus, they argue that

> "*It must be said, therefore, both that the hypothesis of metaphysical determinism has never been as well attested as it is after chaos theory, and that it cannot be made stronger than chaos theory makes it...* Metaphysical determinism and its opposite, it seems, are locked in battle. *There can be no question that chaos theory adds its considerable weight to the side of determinism. However, just as there is the epistemic limitation of self-reference in the study of human existence, and the epistemic limit of the Heisenberg uncertainty principle in the quantum world, chaos theory highlights an epistemic limit in the macro-world of dynamical systems, tethering the deterministic hypothesis even as it advances it.*" (p83, emphasis original)

From this they conclude that

> "Chaos theory also imposes a fundamental limit on how well the deterministic hypothesis can be supported, thus preserving the relevance of chaos theory for forming a philosophy of nature, and assessing the possibility of free divine and human action in accordance with natural laws." (p84)

The implication, then, is that Chaos Theory demonstrates the *possibility* of metaphysical indeterminism. That is,

> "[I]t does open a window of hope for speaking intelligibly about special, natural-law-conforming divine acts, and it is a window that seems to be impossible in principle to close" (p86)

3c. John Polkinghorne: Weak Indeterminism

John Polkinghorne has a PhD in mathematical physics, and is an ordained Anglican priest. He is the author of the books *Quarks, Chaos, and Christianity* (Crossroad Classic, 1996) and *Belief in God in an Age of Science* (Yale University Press, 1998), and of the article "Space, Time, and Causality" (*Zygon,* vol. 41, no. 4, December 2006). Polkinghorne agrees with Russell that Chaos Theory establishes 'epistemological indeterminism,' but he argues further that 'epistemology models ontology:'

> "The intrinsic unpredictabilities in nature, discovered by twentieth century physics first at the subatomic level of quantum theory and then at the everyday level of chaotic systems, offer opportunities to the metaphysician. Unpredictability is an epistemological property, and it is a matter for philosophical debate and decision to conclude what ontological properties are to be associated with it. Those of a realist cast of mind will tend to correlate epistemology closely with ontology, believing that what we know, or what we cannot know, is a reliable guide to what is the case. If this metascientific strategy is followed, unpredictability will be seen as the sign of a degree of causal openness in physical process. In the case of quantum theory, this is indeed the line that has been followed by the majority of physicists, who join with Bohr in interpreting Heisenberg's uncertainty principle as an ontological principle of indeterminism and not merely an epistemological principle of ignorance in the way that Bohm suggests... In the case of chaotic dynamics, however, this approach has been a less popular strategy. This seems to

be at least partly because many take with undue seriousness the deterministic Newtonian equations from which the exquisitely sensitive solutions of chaos theory were first derived. Yet we know that these classical equations cannot be a correct description of the actual physical world. It is entirely possible, therefore, to treat the Newtonian equations as no more than 'downward emergent' approximations to a more subtle and more supple reality." (2006, p979, emphasis mine)

In fact the assumption underlying the determinism of chaotic systems is precisely the assumption proved faulty by the properties of chaotic systems, namely: that the system can be isolated from its environment without effect

"There is, therefore, no valid obligation to adhere to the notion of deterministic chaos. Instead it is possible to be more bold in metaphysical speculation concerning the openness of such systems." (2006, p979, emphasis mine)

Polkinghorne goes on to argue for what he calls 'continuous creation,' suggesting that God is as much creating today as in The Beginning:

"God neither does everything, nor does he do nothing, but he interacts, patiently and lovingly, with the process of creation, to which he had given its own due measure of independence" (1996, p69)

Within certain bounds, then, the cosmos is supple, becoming, and open to the future:

"The sensitivity of chaotic systems means they can never be isolated from what goes on around them. This implies that they can only properly be discussed holistically, that is to say in terms of *all* that is going on... The way they react to small nudges corresponds not to a change in energy (for the nudges can be vanishingly small), but to a change in the pattern of behavior within the confines of possibility represented by the 'strange attractor.'" (1996, p69, emphasis mine)

This then raises the question, "Is God himself open?" to which Polkinghorne replies:

"God knows things as they really are. In a world of true becoming, therefore, will he not know them in their becomingness, that is, in the temporal succession? In other words, if the future is truly open, not just a rearrangement of the past, will not God have to know the world in time, *as it develops*? If this is the case, even God does not yet know the unformed future. This is not an imperfection in God, for the future is not yet there to be known. If this is right, then there must be an experience of time within God, in addition to his eternal nature. Such a conclusion is very controversial, but I believe it to be correct, though not all will agree with me." (1996, p73)

Open Theists have taken up this rally cry, though they have not always acknowledged the subtlety of Polkinghorne's argument. For example, Clark Pinnock, in his book *Most Moved Mover: A Theology of God's Openness* (Baker Academic, 2001), writes:

"In order to supply freedom for the sake of love, God made the world a subtle and supple place... He made creation with purpose and an open future, and a world genuinely contingent, full of creatures capable of free action... There has been a shift in thinking [about the natural world] from mechanistic and deterministic terms to non-deterministic... terms... The beauty is that, given the open view of God, there is no need to deny this shift and every reason to affirm it. Seeing the future as partly open and partly

> settled fits hand in glove with what we are discovering about dynamic systems in science today...God has established a flow of creativity in which there are systems so exquisitely sensitive to circumstances that the smallest disturbance produces large and ever-growing changes in the world. The natural world now seems to be more complex and open than we have assumed... [I]t seems that the path to human freedom lies in nature itself, where God works with and within the indeterminacy of the world... We now recognize factors in nature that make human freedom possible – it is factors like indeterminacy, randomness and uncertainty that create the possibility of flourishing... It is a world which God allowed to make itself to a large degree – a self-making which takes place in a setting of finely tuned potentiality... There are new places of openness for God to move about in and previously unheard ways of understanding how God influences the world, e.g. quantum mechanics, chaos theory, dynamic systems and top-down causation in nature." (p129-131)

Conclusion

In conclusion, then, it seems clear that epistemological indeterminism – at least by humans, finite as we are – has been established by Chaos Theory. As for the question of ontological determinism or indeterminism, the math and the science are inconclusive, and the debate is still open. The issue of divine epistemological (in)determinism – i.e. divine foreknowledge – remains a theological (not scientific or mathematical) question.