GOD, CHAOS, AND THE QUANTUM DICE

by Jeffrey Koperski

Abstract. A recent noninterventionist account of divine agency has been proposed that marries the probabilistic nature of quantum mechanics to the instability of chaos theory. On this account, God is able to bring about observable effects in the macroscopic world by determining the outcome of quantum events. When this determination occurs in the presence of chaos, the ability to influence large systems is multiplied. This paper argues that, although the proposal is highly intuitive, current research in dynamics shows that it is far less plausible than previously thought. Chaos coupled to quantum mechanics proves to be a shaky foundation for models of divine agency.

Keywords: chaos; divine agency; noninterventionist; quantum mechanics.

"If active force should diminish in the universe by the natural laws which God has established, so that there should be need for him to give a new impression in order to restore that force, like an artist's mending the imperfections of his machine, the disorder would not only be with respect to us but also with respect to God himself: He might have prevented it and taken better measures to avoid such an inconvenience, and therefore, indeed, be has actually done it."

-G. W. Leibniz

Although some of the terms in this passage are no longer part of the physicist's vocabulary, the issue addressed by Leibniz endures. This quote is from his famous *Correspondence* with Newton's disciple Samuel Clarke.

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In it Leibniz stakes out a position at the intersection of science and philosophical theology. The question is this: How does the theistic God interact with the physical universe? Clarke had been arguing for the more traditional view in which God intervenes in the natural order from time to time. Some of these interventions are miraculous; others are unobserved physical nudges (say, to keep the planets in their proper orbits). Leibniz argues that Clarke's tinkering God would lack either knowledge or ability. A perfect being would not need to make periodic adjustments to its creation; hence, God does not intervene in the natural order.

Current work on divine agency deems Leibniz's God too passive, too deistic. Whatever the causal joint between God and the cosmos, it must allow for a more active, ongoing governance. On the other hand, Clarke's God is considered by many to be too intrusive, and so the Leibnizian intuition about a tinkering deity continues to shape the debate. Several proposals have been offered as part of a *noninterventionist* program that purports to steer a middle way. Many of these appeal to the probabilistic character of quantum mechanics (see Murphy 1995; Tracy 1995; Russell 1995). According to one version of what might be called a "quantum determination" view of divine agency,

> If there are causal gaps in the ultimate physical processes of the cosmos, those gaps provide space for [divine] intervention that would still be wholly within the boundaries of natural law. For example, God could either bring about or prohibit the radioactive decay of a particular atom at a particular time, but given the way probabilistic laws function, either of those would be totally within the bounds of all of the relevant physical laws. (Ratzsch 1996, 187)

Thus, God can manipulate the ontic probabilities (in contrast to mere epistemic uncertainty) found in quantum mechanics to exercise will in creation without violating any law of nature.

It seems to me--and to others, John Polkinghorne the most prominent among them--that quantum determination (QD) is too limited in scope to provide a robust account of divine agency. (For recent critiques see Polkinghorne 1995; Saunders 2000.) The bottom line is this: QD does not provide sufficient freedom for God to significantly influence macroscopic events. Probabilities enter into the quantum mechanical picture only during the so-called collapse of the wavefunction. Schrodinger's equation itself is completely deterministic. Indeterministic events occur only during measurements, at least on the orthodox interpretation of quantum mechanics that QD advocates (Nancey Murphy, for example) seem to presuppose. The problem is that such events seldom influence macroscopic systems-one of the enduring lessons of the Correspondence Principle. Nonrelativistic macroscopic bodies (almost always) obey classical mechanics, and no amount of quantum manipulation can change that. Hence God's ability to influence the macroscopic world would be quite limited under QD. Granted, these matters deserve a more rigorous treatment, but on the basis of this proto-argument I press on to consider the most promising descendant of this approach.

A recent refinement of QD makes use of advances in nonlinear dynamics (chaos theory). Murphy has taken some very cautious steps in this direction (Murphy 1995, 348-49); Thomas Tracy also leaves the door open but recognizes that there are problems yet to be addressed (Tracy 1995). The idea is that systems displaying sensitive dependence on initial conditions (SDIC) enhance God's ability to work through quantum probabilities: a slight fluctuation determined by God at the quantum level can dramatically affect the evolution of nonlinear macroscopic systems. Let's call this view *chaotic quantum determination* (CQD)[3]. The argument is this:

1. Every material system, including those that evolve chaotically, is ultimately composed of subatomic particles.
2. The behavior of these particles is governed by QM.
3. QM entails the existence of stochastic/probabilistic events rather than the purely deterministic events found in classical mechanics.
4. The outcome of these probabilistic events can produce a change of state in the classical chaotic systems in which the particles are found.
5. God can determine the outcome of these probabilistic events.
6. Therefore, God can determine the future state of every chaotic system.

In this paper I argue that, although CQD is highly intuitive, it rests on questionable assumptions. The first assumption is that nature is sufficiently chaotic for it to be an effective amplifier of quantum fluctuations. Most philosophical and theological discussions of nonlinear systems fail to consider that chaos comes in degrees. As we will see, real-world systems are not as chaotic as one might infer from popular accounts. But if chaos is not as prevalent as CQD advocates believe, then the motivation for moving from QD to CQD is diminished.

Second, I argue that premise 4 is at best oversimplified and perhaps just false. The difficulty lies in a fundamental mismatch between QM and classical chaos, sometimes referred to as *the problem of quantum chaos.* For the amplifying effects of chaos to come into play, quantum events under CQD must have a specific manifestation at the macroscopic level: they must produce a change of state. That such events have this effect on chaotic systems is obvious to CQD advocates. I maintain that tracing the causal chain from one realm to the other is not a simple task.[4] Moreover, if this presupposition proves false, the entire program fails.

Before considering these challenges in detail, let us briefly review why CQD is an improvement over QD.

Chaotic Quantum Determination

Murphy describes QD this way:

> . . . the general character of the entire macroscopic world is a function of the character of quantum events.... We can imagine in a straightforward way God's effect on the quantum event that the experimental apparatus [for Schrödinger's cat] is designed to isolate; we cannot so easily imagine the *cumulative effect of God's action on the innumerable quantum events that constitute the cat's existence.* Yet this latter is equally the realm of divine action. (Murphy 1995, 357; emphasis added)

The picture presented is straightforward: the behavior of the parts (quantum events) determines the behavior of the whole (macroscopic events). Every material object is therefore subject to quantum determination. Just as a sufficient accumulation of snowflakes can eventually produce an avalanche, God's determination of a massive number of quantum events can have observable effects.

The problem is that indeterministic quantum events very seldom influence the behavior of macroscopic objects, for reasons already mentioned. (The subatomic parts of macroscopic objects typically obey the fully deterministic Schrödinger's equation.) The trick for QD is to find a way for God to amplify tiny quantum fluctuations in order to significantly influence the material world. CQD has evolved from QD as a means to bolster this weakness in the causal chain.

For any system evolving chaotically, a slight perturbation will produce a dramatic change in the future state of the system. How slight? When astronomers plot the orbits of the planets in our solar system, they ignore the gravitational pull of everyday objects. Mount Rushmore, my house, and Arthur, our family cat, are simply too small to make a difference. If, however, Arthur suddenly disappeared from the surface of the earth, the gravitational change would significantly affect the motion of Hyperion, the chaotically tumbling moon of Saturn. In principle, even a change on the order of a single quantum level fluctuation on the surface of Hyperion will affect its present state and therefore its behavior over time.

CQD becomes an almost trivial extension of this fact. In a chaotic system, God need not influence innumerable quantum events to bring about macroscopic change. The amplifying effect of chaos allows significant, observable results to be produced from one quantum determination. Under CQD, God need not answer prayers for rain in Texas by miraculously creating a storm front or even by manipulating the collapse of trillions of wavefunctions. If global weather patterns are chaotic, then God need only make a particular quantum event fall one way rather than another, and eventually this act will manifest itself as rain in Austin.

However, as we will see, the in-principle influence of quantum events on chaotic systems loses its plausibility somewhat when more of the physical details ate considered.

Is There Enough Chaos?

In many popular pieces on nonlinear dynamics, we are told that chaos is ubiquitous. Strictly speaking, this is true; there are "more clouds than clocks" in nature, as Polkinghorne often reminds us. However, this claim is also highly ambiguous. In what sense exactly is chaos so prevalent?

The primary answer is mathematical. Since the rise of Newtonian mechanics three hundred years ago, physicists have used differential equations to successfully model natural processes. One of the basic distinctions among differential equations is linear as opposed to nonlinear. If the sum of two solutions to such an equation is itself a solution, the equation is linear. If not, the equation is nonlinear. For various reasons, linear equations are far more tractable than their nonlinear cousins. And because many processes can be approximated using linear equations, physicists and engineers have (until recently) received little training in nonlinear systems.

However, if nature is governed by differential equations, as it seems, then, on purely mathematical grounds, one would expect most systems to be nonlinear and chaotic.[5] Consider an analogy. Among the real numbers, there are clearly many rational ones--infinitely many, in fact. But there are also many more irrational numbers.[6] Intuitively, if one were to pick a real number at random, the odds would be (literally) infinitesimal that it would be rational. This same language is often used to characterize the ratio of linear to nonlinear equations. For example, "If you draw a curve 'at random' you won't get a straight line. Similarly, if you reach into the lucky dip of differential equations, the odds against your emerging with a linear one are infinite" (Stewart 1989,83). Physicist Roland Omnes puts it this way: "From the standpoint of a mathematician, there are many more chaotic systems than regular ones. This means that, if one were to generate the Hamiltoian function at random, the chances would be very high that one would get a chaotic system" (1994,230). Because there is no reason for nature to prefer linear over nonlinear systems, in all likelihood most real-world systems are nonlinear and chaotic. There, in short, is the Argument for Ubiquitous Chaos.

Is this argument sound? On purely mathematical grounds, yes. In the space of differential equations, most are nonlinear. However, as Omnes goes on to say, "nature does not play that kind of game and the majority of ordinary objects around us are not chaotic, except maybe at a very small scale." The point is that, as all theoretical physicists know, armchair mathematical reasoning about differential equations does not necessarily carry over into real-world systems. The prevalence of chaos in nature is an empirical matter and cannot be wholly determined from measure-theoretic arguments about nonlinear equations.

Moreover, the Argument for Ubiquitous Chaos is too strong. If the analogy to the real numbers is as close as it seems, then physicists should never find precise linear equations governing natural systems. If nature is not biased toward linearity, then the odds of finding a realistic linear law or model *are* infinitesimal. To find one such equation would be so unlikely that it would cry out for explanation. But of course researchers in the mathematical sciences do find such equations. For one prominent counter-example, consider this: Schrodinger's equation--which, if anything, counts as a fundamental law of nature--is linear.

Nonetheless, one might still be convinced that the argument is sound even in the face of these remarks. Even so, the royal road to chaos is not yet free and clear. A completely different problem has recently been voiced by one of the fathers of modern chaos theory, physicist David Ruelle. The title of Ruelle’s *Physics Today* piece, “Where Can One Hope to Profitably Apply the Ideas of Chaos?” (1994), is quite puzzling given the rate at which books and articles on chaos have been produced in the last fifteen years. One might think the answer is obvious: “Everywhere.” Among other things, Ruelle argues that chaos is not everywhere, at least not in the way the claim is commonly interpreted. Chaotic dynamics is much like noise: in a given system, there may be a little or a lot (1994, 26). If the chaotic component is small relative to the overall behavior of the system, its presence will have little or no effect.

To illustrate, let us first consider a simple analogy. I recently watched my young son ride his tricycle around a small circle. On each pass around the circle, his wheels seldom if ever went over the exact same path as before. The claim “Marcus is riding in a circle” is accurate but not precise. If one examines his trail up close, there is a good deal of variation. On a large scale, this motion is regular and periodic; on a finer scale, each lap is unique. The point is that, although the path of the tricycle is irregular, this does not entail that the path is completely haphazard. The imperfect, random component in each pass is slight compared to the overall circular figure.

Likewise, to say that a given system is evolving chaotically often means merely that there is a small, random-looking component in the background of a very regular--perhaps periodic--time series.

For another illustration, let us say that during a telephone conversation I detect a very slight hiss in the background. The hiss might be a result of thermal effects in the telephone lines, but it also might be due to deterministic chaos in the network. A dynamical systems analyst may be interested in discovering which is the case, but as for me and my conversation, it does not matter. The hiss is barely detectable. A small amount of background chaos--or background noise--has only a slight effect on the audio signal. The voice harmonics of the conversation dominate the signal. Crudely put, the dynamics is chaotic, but not much.

Real-world chaos is often limited in a similar way. Let’s grant, *pace* Omnès, that strictly speaking chaos *is* everywhere in nature. In many cases, it is present only on the fringes and has little effect on the behavior of a system. Sometimes this is obviously the case. When researchers at the Harvard Medical School argue that heartbeats are chaotic (Ruelle 1994, 26-27), they clearly do not mean to imply that healthy heartbeats are completely erratic. The point of the tricycle, telephone, and heartbeat examples is that the mere presence of chaos in a dynamical system does not entail wholesale disorder. Chaos often shows up only in the background of an otherwise regular evolution. It comes in degrees, just like thermal noise.

The motivation for adding chaos to simple QD is that a small change at the quantum level can in principle produce a large change in the evolution of a nonlinear system. Ruelle's point is that the large change is dependent on the scale at which one considers the dynamics. Consider the telephone illustration again and assume that CQD is true. God could thereby exercise complete control over the chaotic portion of the signal. Unfortunately, complete control here amounts to very little. Divine manipulation of the low-level chaotic hiss would have no noticeable effect on the conversation, and so the extent of God's influence over this system is quite limited. If most real-world chaos is likewise restricted to the periphery, then CQD cannot provide significantly more leverage for God's action than QD does.

Cambridge philosopher Peter Smith has recently noted another often-ignored restriction on SDIC in nature. He argues that the presence of chaos in dynamical systems requires other sorts of constraints in order to get off the ground. Consider the paradigmatic Lorenz model and the butterfly effect. In 1963 meteorologist Edward Lorenz proposed a rough mathematical model for the behavior of convection cells in the atmosphere. Numerical simulation of this model unexpectedly revealed SDIC. On the basis of this result, researchers have tentatively concluded that the weather is chaotic. Smith quotes a typical summation from Stewart:

> Lorenz realized that his equations weren't behaving the way a traditionally-minded mathematician would expect Lorenz coined his famous phrase: "butterfly effect." The flapping of a single Butterfly's wing today produces a tiny change in the state of the atmosphere. Over a period of time, what the atmosphere actually does diverges from what it would have done. So, in a months time, a tornado that would have devastated the Indonesian coast doesn't happen. Or maybe one that wasn't going to happen, does. (Stewart 1989, 141)

Smith then points out that an important shift has taken place in the course of this exposition of Lorenz's discovery-a shift that I believe is quite common.

> Even if we ignore for the moment the empirical short-comings of the Lorenz model, how on earth are *tornadoes* supposed to get into the story? The model was intended to describe the behavior inside one of a series of parallel horizontal convection rolls: and it actually counts *against* butterfly-sized causes producing tornado-like effects. For the model assumes that the large-scale pattern of rolls, laid side by side like so many felled logs, remains entirely stable: the chaotic behavior is local, as the rolls change their rotation-speeds in never repeating patterns. . . . [S]o long as we are still working within the Lorenz paradigm, there is no destructive break-up

of the rolls, no wildly accelerating convection, and hence certainly no tornadoes! (Smith 1999,67)

The point is that chaos in the atmosphere does not imply that "anything goes" vis-à-vis the weather. Lorenz's model presupposes a stable layer of convection cells. A butterfly's wings would clearly perturb the random-looking rotation within a given cell, but this moderate effect is a far cry from storm fronts and tornadoes. In fact the latter would destroy any convection cells, rendering the model inapplicable. Once again, it is strictly speaking true to say that weather patterns are chaotic: there is a meteorological phenomenon that displays SDIC, assuming the model is realistic.[8] However, this fact does not support the kind of broad extrapolation one generally sees in discussions about chaos and the weather.

The upshot for CQD is, again, that the mere presence of chaos in a physical system might not amount to much. The Lorenz model provides no justification for the claim that a butterfly outside my window can change the weather in Indonesia. The same goes for the analogy of the butterfly in the CQD scenario--quantum determinations (i.e., the motion of the butterfly's wings) is what perturbs the state of the atmosphere; the outcome of the quantum determination is what perturbs the state of the generic nonlinear system for CQD. Of course, those who think that God can influence the weather via chaos do not believe that this influence is limited to convection currents. They believe that God can determine the state of global weather patterns. My point is that the evidence for meteorological SDIC does not support their view. Chaos at the level of Lorenzian convection is restricted and has little obvious effect on full-blown weather systems. (Compare this to the heartbeat example. The conclusion is the same: the presence of chaos may have no effect on the dominant evolution of the system in which it is found.)

In sum, the idea that nature is overwhelmingly chaotic is easily detached from the mathematically grounded science that first introduced it. Like "artificial intelligence" and "virtual reality," "chaos" is a highly suggestive rubric. It is common to think of it as complete turmoil, disorder, and unpredictability. The truth is somewhat disappointing. Chaos comes in degrees and often is found in the midst of stable structures (e.g., convection cells) and dynamics that are predominantly regular (e.g., heartbeats). But this kind of circumscribed chaos works against CQD. If CQD is correct, then in whatever manner SDIC is restricted in nature, God's influence would be restricted to the same degree. Most theists will take this consequent to be unacceptable. Simple modus tollens tells us that something must be wrong with CQD.

One might argue that, even if all of this is correct, nature is still sufficiently chaotic to make CQD an interesting program. The challenges presented thus far limit the scope of this causal joint, but the joint itself is still intact. In the next section we examine a more foundational problem, one that questions the very possibility of quantum fluctuations influencing the evolution of macroscopic, chaotic systems.

THE QUANTUM SUPPRESSION OF CHAOS

An important and interesting clash between chaos theory and QM has been dubbed "the problem of quantum chaos." To start with, physicists cannot predict the onset of classical chaos using QM alone. This is not surprising. It is often difficult and sometimes impossible to derive the properties of macroscopic objects simply by looking at their microscopic constituents (a truth that has contributed to the gradual demise of reductionism). However, one does expect the laws governing the constituents *to permit* what is observed at the macroscopic level. Even if the relation between the two realms is poorly understood, they are expected to be (at the very least) logically consistent. For example, geneticists may not be able to tell that a given DNA sample came from a penguin, but, given a sample of penguin DNA, we would expect genetic analysis to allow it as a possibility. If DNA testing is trustworthy, it should not *disallow* the possibility that the sample came from a penguin when we know that it did. If that were the case, it would present a clear challenge to the theory and procedures used in genetic analysis.

For that reason, even though QM does not indicate when a system will behave chaotically, one would at least expect classical chaos to be compatible with QM. Surprisingly, it is not. In this case, the more fundamental, microscopic theory (QM) disallows what is observed in larger, classical systems (chaos), an effect physicist Michael Berry calls "the quantum suppression of classical chaos" (Berry 1987, 184). There are a number of ways to present the problem, but one way in particular is more precise than the rest.[9] Succinctly, it is this:

> For bounded systems . . . neither the quantum wavefunctions nor any observable quantities can show the extreme sensitivity to initial conditions that defines classical chaos. The quantum mechanical energy spectrum is discrete, and the solutions of the Schrödinger equation restrict the quantum dynamics to quasiperiodic behavior, whereas the corresponding classical dynamics can be fully chaotic. (Jensen 1992, 312)

In short, the most complex behavior allowed by QM is quasiperiodicity, which is a step below full-blown chaos. Let's now consider what all this means in less technical terms.

In order to understand the problem, we must work our way toward quasiperiodicity-an imposing term with an intuitive, geometrical meaning. To start with, state spaces are used in dynamics to represent the state of a system and its evolution. The system is often a physical model, like an ideal pendulum. Solutions to the ordinary differential equations used in chaos theory are conveniently represented in n-dimensional *phase spaces*. Points in these (usually Euclidean) spaces represent system states. As the state evolves over time, a trajectory is carved through the space. Every point belongs to some possible trajectory that represents the evolution of the system over time. A phase space together with a set of trajectories is called a *phase portrait.* Figure 1 (a) and (b) are distinct phase portraits for two different systems; the lines represent some of the possible trajectories.

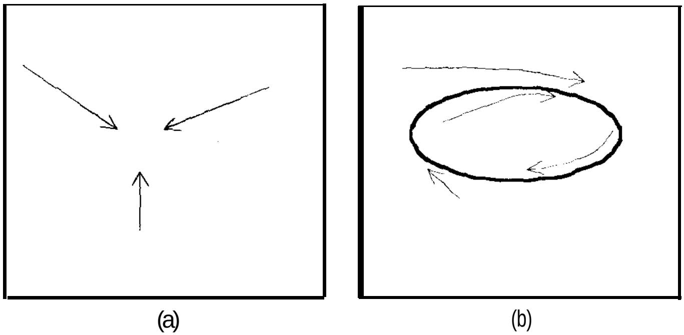

Fig. 1. Sample phase portraits

Different kinds of dynamical behavior produce correspondingly different structures in phase space. Simple periodic motion in one spatial dimension10 has a characteristic frequency, ω. In its phase space representation, such motion is captured by a closed loop, also known as a l-torus. If a system oscillates in more than one spatial dimension, it will have two associated frequencies, ω_1, ω_2. Quasiperiodic motion occurs when ω_1 and ω_2 are rationally incommensurable. Phase space trajectories for this type of motion are restricted to the surface of a 2-torus (fig. 2). Each trajectory will wrap itselfaround the “doughnut.” The spacing of the wrapping bands depends on the values of ω_1, ω_2.

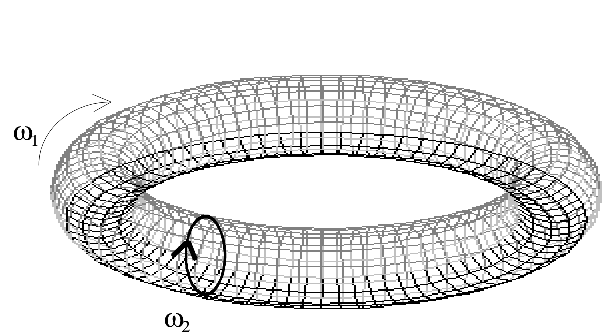

Fig 2.: 2-torus

Phase portraits for (conservative) chaotic systems are strikingly different. No discernible geometric structures appear." Trajectories in a chaotic phase portrait are not restricted to tori but instead wander through most" of the phase space. (This lack of structure in the phase portrait is directly related to the randomness associated with chaotic behavior.)

For our present concerns, the key point is this: quasiperiodicity is a category of dynamical behavior distinct from chaos. This difference is evident in their respective phase portraits (tori vs. unrestricted wandering throughout the space). If a system displays quasiperiodic behavior, it cannot at the same time be chaotic. Chaos is a full step beyond quasiperiodicity vis-à-vis complexity of motion. Let's now consider how these categories of dynamics apply to QM.

Unlike the ordinary differential equations that govern the behavior of classical chaotic systems, QM systems are governed by Schrödinger's equation, which in its time-dependent form is

$$(1)\ i\hbar \frac{\partial}{\partial t} \Psi(\mathbf{q},t) = \hat{\mathrm{H}}\Psi(\mathbf{q},t)$$

The general solution for (1) is

$$(2)\ \Psi(\mathbf{q},t) = \sum_n c_n|\varphi_n\rangle \exp\left(\frac{-i}{\hbar}E_n t\right)$$

(where $|\varphi_n\rangle$ are the eigenstates of $\hat{\mathrm{H}}$, and E_n are its eigenvalues). Without going into the mathematical details, (2) entails that (i) the state of the quantum system, captured by $\Psi(\mathbf{q},t)$, can evolve periodically or quasiperiodically (Jensen 1992), and (ii) the expectation value of any observable for this system will likewise be restricted to periodic or quasiperiodic evolutions (Batterman 1993). QM systems *cannot,* therefore, reach the next level of dynamic complexity: chaos. In his exposition of these results, Batterman concludes,

> [D]espite the fact that there is a formal correspondence between the classical Hamiltonian and the quantum Hamiltonian operator . . . *a finite and bound quantum system governed by the Schrödinger equation cannot exhibit the sort of sensitive dependence on its initial state characteristic of the classical chaotic system.* (Batterman 1993; emphasis in original)

Difficult questions immediately arise. If QM is true and yet it blocks the onset of chaos, how is chaotic behavior possible? Is chaotic dynamics merely an approximation, limited to a validity domain like ray optics? Is chaos theory merely an interesting artifact of differential equations and computer simulations? Or, as Joseph Ford suggests (1989), is there something fundamentally wrong with QM?

Much progress has been made on the nature of this surprising tension. The "big question" about how to resolve the conflict, however, has been put on hold. Few physicists are presently trying to figure out how quantum mechanics might permit classical chaos. Researchers have instead come to accept the uneasy coexistence of the two realms as a given, on a par with the well-known conflicts between QM and general relativity. Symposia on quantum chaos have shifted their focus away from finding chaos in QM toward the discovery of coextensive properties between the two realms. This search has yielded several dynamical properties in quantum and semiclassical systems that occur when (and only when) the corresponding classical system is chaotic (Jensen 1992; Gutzwiller 1992; and most recently the Drexel Symposium on Quantum Nonintegrability 1997).[13] Berry prefers to call this search for counterparts between the quantum and classical domains "quantum chaology," since it seems there really is no such thing as quantum chaos. The hope is that one day the nature of the conflict itselfwill be understood. That day is not on the horizon, however.

In short, the quantum suppression of chaos has largely been abandoned, at least for now. Work continues on the more tractable question of dynamical properties that are coextensive in the classical and quantum realms. For our purposes, the key point is that some dynamical properties in macroscopic systems (e.g., chaos) are not found in their QM analogues. Likewise, some of the limitations on dynamical behavior in QM systems (e.g., the quasiperiodic ceiling) are not observed at the macroscopic level. A given dynamical property at one level may have counterparts in the other, but that is an empirical question. The existence and nature of such counterparts cannot be determined a priori. As I will explain shortly, CQD advocates have either missed or ignored this point.

Application to CQD

We may now say more precisely how CQD envisages the effect of quantum determinations within a macroscopic system. Indeterministic, quantum-level events determined by God change the state of the system, bumping it from one phase space trajectory to a near neighbor, which then exponentially diverges from the original in phase space. The future states of the system are now completely different from what they would have been-once again, rain rather than sun in Austin on a given day.

The upshot of the last section is that this story contains a hidden premise. Specifically, it is assumed that we know how QM properties will manifest themselves in macroscopic systems. But we do *not know*, at least not when the system is chaotic-the one crucial case for CQD. The lesson of quantum chaology is that the properties of chaotic systems often have counterparts in the QM realm and vice versa, but these counterparts are often *qualitatively different from one another.* Hence, even if quantum determinations can affect classical chaotic systems, it is not clear that they will manifest themselves as a change of state in phase space.

In other words, no one can say at present what the realization of a divinely determined quantum event would look like in a chaotic system. In particular, it is not clear whether these determinations would bring about a change of state at the classical level, but that is precisely the effect they must have for CQD to apply.

To be fair, I have not shown that quantum determinations cannot cause a change of state in a chaotic system. However, the onus is on the CQD advocate to show that quantum determinations do have this effect. If these quantum events manifest themselves in some other manner (i.e., if their counterparts are not a change of state), then CQD is blocked. To date, CQD advocates have assumed that microevents will play a specific causal role from QM up through astrophysics. As I have argued, this seemingly small detail relies on quite a bit of unsubstantiated armchair science and ignores research that suggests the truth is something far more subtle.

CONCLUSION

The challenge for QD is to try to do more with less. Random quantum events are washed out in the macroscopic realm and cannot serve as the foundation for a sufficiently rich model of divine agency. The appeal to nonlinear dynamics is an attempt to amplify these events. I agree that CQD is a natural move for Murphy, Tracy, and others to make. But as I have tried to show, this move is far more difficult to carry out than one might imagine. To sum up, my critique has two prongs.

First, following Omnès, Ruelle, and Smith, nature is not as chaotic as many informal expositions imply. Even if we grant that most systems are nonlinear (and therefore *possibly* chaotic), aperiodicity and randomness are dynamical characteristics that often reside in the midst of perfectly regular evolutions. Chaos, like background noise, is routinely ignored and rightly so. The problem is that CQD needs nonlinear evolutions to be very much in the foreground. For God to make effective use of chaos, it must influence the large-scale, dominant behavior of a system. However, this is often not the case. To put it crudely, CQD describes a causal pathway in which God could alter the arrangement of bubbles in the crest of a tsunami but not redirect its course. Presumably more is wanted from an account of divine agency.

Second, quantum chaology shows that even if quantum events do manifest themselves classically, one cannot determine by inspection the form in which they will do so. Quantum determinations *might* produce a state change in the corresponding chaotic system. They might also change a parameter value knocking the system out of the chaotic regime and into an evolution lacking SDIC. A variety of alternatives can be imagined. The burden of proof falls on CQD to show that the effect is the one required for this to be the causal joint of divine action.

At the end of the day, I cannot claim to have refuted CQD. I have shown, however, that the program has written some very large promissory notes that in all likelihood will not be cashed out.

NOTES

I would like to thank John Polkinghorne for his encouragement and helpful comments on early drafts. Thanks also to an anonymous referee for several suggestions.

1. Measurement is a notoriously imprecise term, but one that has been widely adopted to describe events that prima facie have little to do with experimental measurements. See, for example, Albert 1992.

2. Those who are committed to a view of the measurement problem whereby a vast number of indeterministic quantum events are able to influence macroscopic objects will find this move into chaotic dynamics unneeded. I do not wish to pursue that matter here. My argument is addressed to those who hold a more traditional view of quantum measurements and are actively seeking a means to amplify their effects.

3. Polkinghorne (1996, 37) calls this "the hybrid project." I agree with Polkinghorne that, although CQD has few prominent advocates in print, it is nonetheless a common view that continues to gain advocates as the weaknesses of quantum determination are recognized. My goal is to try to close off this exit before the migration begins so that research may turn toward more promising proposals.

4. Although these problems have been alluded to elsewhere, the response has been rather sanguine. In contrast, I think the correct attitude is pessimism. One especially clear discussion is in chapter 3 of Polkinghorne 1991. Also see Young 1996.

5. Not all nonlinear differential equations are chaotic, but we may gloss over that distinction for now.

6. Technically, the set of irrationals in some interval is an uncountably infinite set, whereas the rationals are countable.

7. Thanks to James Sennett for helping me to clarify this point.

8. It almost certainly is not realistic. The mathematical simplifications used in order to derive the Lorenz model are extreme. In fact, the partial differential equations Lorenz started with are not themselves chaotic! See Lichtenberg and Lieberman 1983, 446, and for a more philosophical discussion Koperski 1997, 110.

9. A less precise but somewhat more intuitive approach considers the geometric properties of chaotic attractors. Stewart (1989,295) puts it this way: "Classical chaos involves fractal attractors, that is, structure on all scales. But in quantum mechanics . . structure does not exist on a scale smaller than Plank's constant. So quantum effects smooth out the fine detail so necessary of true chaos." See also Hobbes 1991, 159.

10. An example would be an ideal mass-spring system on a frictionless surface.

11. Phase portraits for dissipative chaos do have a unique geometric structure, viz., the fractal geometry of a strange attractor. In both conservative and dissipative systems, the point remains that quasiperiodicity and chaos are qualitatively distinct.

12. In a conservative system with N degrees of freedom, each trajectory in the 2N-dimensional phase space will wander throughout a surface of constant energy with dimension 2N-1.

13. It has been shown that the distribution of quantum energy levels (spectra) is different in QM systems with integrable rather than chaotic counterparts. Classical systems that are integrable (and therefore not chaotic) have quantum counterparts with randomly distributed energy spectra. Classical chaotic systems have quantum counterparts with highly correlated energy spectra. As Gutzwiller (1992) points out, this is a paradoxical result. A priori one would expect chaos to produce randomness at the QM level, not correlations.

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