Article

# Chance for a Purpose

*John W. Hall*

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*In our popular understanding, chance implies a lack of purpose. Consequently, the presence of chance or stochasticity in some physical and biological processes has led to the inference that the universe has no purpose. But we ourselves construct systems with stochastic features for our own uses. Several such systems were investigated to elucidate how the set of possible outcomes of a stochastic process is related to the global and local purposes of the system. One observation is that when every possible outcome is compatible with a particular purpose, the outcomes may be described as "purpose-equivalent." This and other insights are used in investigating the relationship of two created systems with what we know of God's purposes. These are the physical processes that produced the distribution of matter in the universe and biological evolution. How stochastic processes relate to other forms of divine action is also discussed.*

The title of this article "Chance for a Purpose" seems contradictory. Was it not by chance, that is, without it being his intention or purpose, that the Amalekite encountered King Saul on Mount Gilboa with such disastrous consequences?[1] Such an account reflects our popular understanding. Chance implies a lack of purpose. Consequently, the use of chance to describe some physical and biological processes has been interpreted as implying a lack of purpose in the universe as a whole. Yet we ourselves construct systems incorporating chance processes and put them to our own uses.

In this article, several such systems will be examined to see how their processes relate to their purposes. With these insights we can proceed to examine chance processes in physical and biological systems and consider how they may relate to God's purposes and actions. But first, the concept of chance needs to be scrutinized further.

## Chance and Stochasticity

In his investigation of chance in God's world, philosopher Peter van Inwagen described chance this way:

> What I shall mean by saying that an event is a "chance" occurrence, or a state of affairs a "matter of chance" or "due to chance" is this: The event or state of affairs is without purpose or significance; it is not part of anyone's plan; it serves no one's end; and it might very well not have been.[2]

Here van Inwagen identifies chance with a lack of purpose. Chance events, though they occur, are not part of God's plan.

Non-Christians draw even stronger conclusions. Perhaps this was expressed with the greatest clarity by the late Nobel prize-winning biologist Jacques Monod. His book *Chance and Necessity*, which describes his understanding of the interplay between these two features in modern biology, famously concludes:

*We [will] examine chance processes in physical and biological systems and consider how they may relate to God's purposes and actions.*

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> The ancient covenant is in pieces; man knows at last that he is alone in the universe's unfeeling immensity, out of which he emerged only by chance. His destiny is nowhere spelled out, nor is his duty. The kingdom above or the darkness below; it is for him to choose.[3]

For Monod, then, the presence of chance means that there is no God. Humans are alone. But this conclusion, darkly as he paints it, leads him not to despair but to anthropocentrism in its modern form. Humanity, in this view, is free to choose its own destiny.

Despite challenges, Monod's view has persisted.[4] Philosopher Daniel C. Dennett's rhetoric leaves no uncertainty when he calls natural selection a "mindless, purposeless, mechanical process" and a "universal acid" and refers as well to "the mere purposeless, mindless, pointless regularity of physics."[5] Dennett's universal acid includes chance variation. The possibility that this variation may sometimes be the result of quantum effects satisfies philosophers like David N. Stamos and Alex Rosenberg, that no reconciliation with design, and hence with purpose, is possible.[6] Referring to Dennett's "universal acid" as the "solvent algorithm," Sommers and Rosenberg write: "The solvent algorithm deprives nature of purpose, on the global and local scale."[7]

So pervasive is the association of purposelessness with chance that I propose to abandon the term and use "stochastic" to describe what we are considering instead. A stochastic process is one for which there is more than one possible outcome and the outcome that actually occurs cannot be predicted with certainty. For many such processes, the set of possible outcomes is associated with a probability distribution. The question of whether a stochastic process, or the system of which it is a part, has any purpose cannot be prejudged. The answer must be determined by studying the system itself and any purposes claimed for it.

A familiar example of a stochastic process is radioactive decay. The rate at which a sample of a radioactive isotope decays is equal to the amount of the isotope present multiplied by a constant that is a characteristic of the isotope. For samples containing large numbers of atoms of the isotope, the average amount remaining over time is described by an exponential function. But the process is stochastic because the time at which any particular atom decays is unpredictable, as is the number of atoms that will decay in a given time interval. For time intervals in which only a small amount of a sample decays, the number of atoms decaying is described by the Poisson probability distribution.[8]

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Radioactive decay is a quantum process and consequently seems essentially stochastic. That is, no one has discovered any underlying mechanism that produces the phenomenon. What is more, entanglement experiments have shown that the presence of hidden variables is incompatible with the assumption of locality, that measurements on a system localized in space-time cannot be instantaneously influenced by a distant event. The implications of these experiments are far-reaching and continue to be actively investigated.[9]

Other processes can generate stochastic outcomes. Over the past several decades, there has been much interest in chaotic processes. These processes produce outcomes that are neither essentially stochastic nor easily predictable.[10] One notable feature of a chaotic process is its sensitivity to initial conditions. Small changes in initial conditions lead over time to widely divergent outcomes.

Mathematical models of chaotic processes are deterministic rather than stochastic. Given the same initial conditions, a chaotic process operating in isolation produces the same results. Moreover, examination of the phase diagram for such a process can reveal nonstochastic patterns called strange attractors. For some chaotic processes, however, these patterns can be hard to identify, and real processes do not operate in isolation.

The lack of isolation can have dramatic consequences for dynamic systems. On average, each molecule in the air experiences fifty collisions in less than a microsecond. But the accurate prediction of the trajectory of an air molecule after fifty successive collisions must take into account the gravitational effects of the electrons at the edge of the observable universe.[11] Because of this universal dependence, the complete set of initial conditions will never reoccur.

The phenomena that we will consider are produced by multiple processes interacting with each other under conditions that are not tightly controlled. Consequently the initial conditions will not be specified precisely and will become irrelevant as the processes repeatedly interact. Under these conditions, the outcomes are effectively stochastic.

With these ideas in mind, we are ready to consider the nature of purpose in three humanly constructed systems with stochastic features: ice hockey, lotteries, and certain experimental designs used in scientific research.[12]

## Constructed Systems with Stochastic Features

### Ice Hockey

The game of hockey is played by two teams skating on a sheet of ice with a goal net at each end. Six players of each team may be on the ice at a time and the objective of the game is to shoot a hard rubber puck into the opposing team's goal. The goal is guarded by a player called the goalie and the puck is controlled using hockey (hooked) sticks. Professional matches are played over three twenty-minute periods. At the end of the match, the team that has scored the most goals wins, with ties being possible. In professional games, scores are rarely above single digits.

Two factors govern which team will win a particular match. First is the relative strength and skill of the two teams, the better team being more likely to win. Second is a stochastic element. This includes the bounce of the puck, the roughness of the ice, the position and speed of the stick when a shot is made on the goal, and the positions of all the players, especially the goalie, at the time of the shot. In the professional National Hockey League (NHL), the stochastic component of the scores is well described by the Poisson distribution, the same one that describes radioactive counts.[13]

The NHL, in a single season, forms a system whose purposes can be investigated. To simplify the discussion, consider an earlier era when the league had only six teams. Each team played seventy regular-season games, playing every other team fourteen times. At the end of the season, the results showed that there were differences among the teams. Attempts were made to increase the effect of the stochastic element by trading players among teams to even up their relative strengths. What made the sport exciting for fans was that "on any given night any given team can beat any other team."[14] This possibility ensured the interest of the fans, producing good attendance at the games and putting a profit in the team owners' pockets. A primary purpose of the NHL, a "global" purpose of the system, was to make a profit for the owners. Ensuring that the outcome of a match had a large stochastic component was not purposeless but contributed to this global purpose.

However, this is not the whole story. In a single match, each team wants to win and, ultimately, to advance to the playoffs to earn financial bonuses. At best, only one of the two teams achieves this "local" purpose. Thus, while it contributes to the global purpose, the stochastic nature of the game either frustrates or serves the more restricted, local purpose of an individual team. Because they serve global purposes, all possible outcomes of a match may be said to be "purpose-equivalent." But only a subset of outcomes, those leading to a win, serve the local purpose of an individual team.

In order to identify other features of such systems, it will be useful to have another example in mind. A lottery provides such an example, but in examining lotteries, I will set aside any ethical issues concerning them.

### Lotteries

In the 6/49 lottery that is run in my province, the set of possible outcomes is made up of all the combinations of six different numbers between one and forty-nine. The grand prize is divided among the holders of tickets whose six numbers match the winning combination. A seventh number, "the bonus," along with partial matches to the winning combination, are used to award subsidiary prizes. These will be ignored for the sake of simplicity. The profits from the lottery go to the provincial governments that own it.

Each time the lottery is played, the winning combination is determined by a mechanical device consisting of a rotating sphere containing forty-nine balls, each ingrained with a single number. Arms within the sphere and rotating in the opposite direction to it agitate the balls, and after a period of time that varies from draw to draw, six balls are released from the sphere, one by one. The order in which these balls are released is ignored, and the numbers on them form the winning combination. As in hockey, the process which generates the outcomes is chaotic rather than essentially stochastic, but the results are effectively stochastic. Great care is taken to ensure that the process is stochastic so that the lottery will be perceived to be fair by the participants.

The global purpose of the lottery system is to make a profit for its owners. This is achieved no matter which combination of numbers occurs in any single draw. Thus, the approximately fourteen million possible combinations form a set of outcomes that are purpose-equivalent with respect to the global purpose of the system. Each participant also has a purpose, that of winning, but this local purpose is served only if the outcome belongs to a small subset of all the possibilities. The local purposes of individual participants are much more likely to be frustrated than to be fulfilled.

From these two examples, the main features of systems incorporating stochastic processes can be identified. Unlike a deterministic process, a stochastic process does not produce a single predictable outcome, but the outcomes are restricted to certain sets of possibilities. Wishing to wager on 51 or √2 in the 6/49 lottery is useless, and even when the geometers play the algebraists, the score will never be "π – e."

When the lottery was designed, the outcome set was consciously decided on, and it contains a fixed number of possibilities. By contrast, hockey developed informally and there is no fixed number of possible scores. Nevertheless, scores in professional games are usually in the single digits, the most goals ever scored in total in an NHL game being twenty-one.[15]

Systems that are very similar may have different purposes. A game of hockey in a recreational league is similar to a professional one. But in the recreational league, no one makes a profit. As well as wanting to win, the motives of the recreational players may include getting exercise, meeting a challenge, and enjoying the camaraderie of their teammates. Professional players also enjoy exercise, challenges, and camaraderie, but satisfying these motives is the primary purpose of the recreational league.

Global purposes are distinguishable from local ones. Any outcome from the system contributes to a global purpose, but only a subset of outcomes fulfils a local one. For global purposes, all the outcomes are purpose-equivalent, but they need not be equally probable. All the possible six number outcomes in the 6/49 are equally probable, but in the NHL, low scores are more probable than high ones.

## Experimental Design

In scientific research, designs with stochastic features are used in comparative experiments in which the treatments being compared are applied to subjects that are either whole biological organisms, like mice, or groups of organisms, like field plots of raspberries.[16] In simpler designs, each subject receives a single treatment. But even when the subjects come from a homogeneous population, such as an inbred strain of mice, responses to the treatments can vary considerably from subject to subject. If further steps were not taken, the results of such an experiment would be ambiguous. Should the observed treatment differences be attributed to the treatments themselves or to differences among the subjects receiving them? This problem is addressed in two ways. First, each treatment is applied to multiple subjects. Second, subjects are assigned to treatments randomly, that is, by a stochastic procedure. The name of one of the most commonly used designs, the "randomized complete block design," reflects this.

Stochastic assignment allows the effects of the treatments to be distinguished from differences among subjects. It also provides a measure of how precisely treatment effects have been determined and how strongly the conclusions from the experiment should be held.

The research program of which the experiment is a part is the system under consideration. A single experiment is analogous to a single season game in the NHL. The actual stochastic assignment used in the experiment is drawn with equal probability from a set of possible ones. This set may exclude some assignments that might reflect patterns among the subjects. In experimental design, all the possible stochastic assignments fulfil the researcher's global purposes and are purpose-equivalent. There are no local purposes to be frustrated or fulfilled.

These examples serve as model systems that provide the concepts for understanding more complex situations. This allows a re-examination of van Inwagen's understanding of chance. When he said that a chance occurrence was without purpose and served no one's end, he appears to have been thinking exclusively of local purposes. Thus his statement makes sense when applied to questions such as, "Why did their team win when our team is just as skilled?" His paper was a prelude to addressing the problem of evil, a difficult subject well beyond what is being considered here.[17] However, in one of his examples, he discussed God's decree about the initial arrangement of particles in the universe. There he wrote: "Well, suppose there are various alternative initial arrangements that would suit God's purposes equally well."[18] Surely this describes a set of purpose-equivalent outcomes in all but terminology. This leads to the consideration of physical and biological systems which behave stochastically, and their relation to God's purposes. We will limit our attention to one physical and one biological system.

## Created Systems with Stochastic Features

### Distribution of Matter in the Universe

The observable universe is estimated to contain about one hundred billion galaxies, each containing, on average, one hundred billion stars. This is a lower bound for the size of the actual universe which stretches beyond what we can observe. A notable feature of the current distribution of matter that has been discovered by large-scale astronomical surveys is its filamentous character.[19] These filaments, which form a "cosmic web," contain matter at higher concentrations than elsewhere and are the locations of the galaxies and stars.[20]

Studies of the cosmic microwave background radiation, which reflects conditions in the early universe, indicate that in the earliest times the distribution of matter was highly homogeneous and isotropic though not completely so.[21] The distribution had tiny stochastic fluctuations in density. These fluctuations acted as seeds that were modified by acoustic oscillations and amplified by gravitational collapse to form the cosmic web. The consequence of these stochastic fluctuations is a rich variety of galaxies and stars and at least one place in the universe that is hospitable to organic life.

The stochastic nature of the fluctuations suggests that the exact distribution of matter in the universe was not fixed. What we observe is a single outcome from a vast set of possibilities, all of which would have produced the large-scale features that we observe, but not the exact details. This leads to the question of whether, when God's purposes are considered, this is a set of purpose-equivalent outcomes. Before attempting to answer this question, the second example will be introduced.

### Biological Evolution

The probability that an organism of a particular species will reproduce depends on how well it functions in its environment. This reflects both antagonistic and synergistic interactions with other organisms of the same and of different species, as well as its interaction with its physical environment. No organism is certain to reproduce, and organisms in a population of the same species in the same environment have different probabilities of reproductive success. This, in modern terms, is what Darwin named "natural selection" by analogy with artificial selection or breeding.

How well an organism functions is related to its genome, which is composed of chains of four different nucleic acids that in the cell nucleus are organized into chromosomes. These chains of DNA contain the codes for proteins, for RNA molecules with other functions, and for regulatory sequences. When the chromosomes are reproduced in cell division, various kinds of changes or mutations can occur. These include additions, deletions, or substitutions of single nucleotides; and deletions, insertions, inversions, and copy number changes in longer stretches of DNA that may contain whole coding regions.[22] At the chromosomal level, possible changes are fusion of chromosomes, inversion of large segments around the centromere, and polyploidy.[23] The latter is most frequently observed in the flowering plants (angiosperms).[24] These mutations vary in amount of DNA involved, frequency of occurrence, and effect on the viability of the resulting organism.

Mutations have chemical and physical causes, possibly including quantum effects.[25] But although the biological functioning of an organism is dependent on its underlying biochemical processes, the two are in some sense "decoupled." The biological functioning of the organism may be said to "supervene" on the underlying biochemical processes.[26] Because of decoupling, mutations are not directed toward any predetermined change in biological function. Their rarity, unpredictability, and lack of biological direction mean that they occur stochastically. This stochastic variation along with natural selection is believed to be the predominant process for producing changes in species over biological history.[27]

During the earth's history, the physical environment has varied widely because of plate tectonics, large-scale vulcanism, and meteoric impacts. Wide fluctuations have occurred in planetary temperature and atmospheric composition. These changes alter the probabilities of reproductive success of organisms, and result in the modification or extinction of old species and the generation of diverse new ones.

This diversification is offset by the widespread occurrence of convergence.[28] Species with varied histories that fill similar ecological niches may differ greatly in detail, especially biochemically, but converge to similar biological features. Compare, for instance, the whales, mammals that returned to the sea, with the fish that never left it.

The stochastic nature of these processes, along with adaptation and convergence, result in three features of biological life. First is its rich, though not unlimited, diversity. The outcome set of this system is large. Over biological history there have been so many different species that it is unlikely they could have all flourished at the same time. Second is its harmony. Most of the time species are well adapted to their environments. Third is its persistence. Even when catastrophes have wiped out most species, some have always survived to diversify and replenish the earth once more.

Both the distribution of matter in the universe and biological evolution involve processes that are stochastic. Both have large sets of outcomes. But are they consistent with any purpose? To answer this question we must investigate what we know of God's purposes in creating the universe.

## God's Purposes

To determine God's purpose in creating the universe, our first impulse might be to turn to Genesis 1. But this account reads, albeit anachronistically, like a set of executive minutes. It presents decisions made, actions taken, and evaluations of the results. However, it records neither motives nor long-term objectives. The immediate purpose, that of creating a universe, can be inferred from the actions, but why the universe was created is not stated.

As salvation history unfolds, God's purposes are gradually revealed especially with regard to ourselves. Thus, in the familiar John 3:16, we have, "For God so loved the world [motive], that he gave his only begotten son [action], that whoever believes on him should not perish but have everlasting life [purpose]." Salvation begins with the individual, but it does not end there. In John 17:20–26, Jesus prays that all believers may be one as he and the Father are one. This prayer reflects the unity and glory of the Trinity and desires a similar unity for the church. It anticipates the end of history when our communion with the Trinity will be complete and will, in some way, reflect its own internal relationship. However, God's purposes extend further than this.

Biblical revelation focuses to a great extent on us, but God's purposes extend beyond us to the whole of the universe, vast as it is. As Paul says in Rom. 8:20, "the creation itself will be liberated from its bondage to decay." Reflecting on this passage in light of the whole biological creation, chemist Walter Thorson has written:

> From the very beginning, God has deliberately *intended* that all his creatures shall participate, with the various capacities each has, in a "glorious liberty"; otherwise we can make no more than poetic sense of Romans 8:18–25 in relation to the non-human creation.[29]

Why then did God create the universe? This question was studied by the eighteenth-century theologian Jonathan Edwards, whose answer could not have been influenced by modern accounts of cosmology or biology. After an extensive review of Scripture, Edwards concluded that ultimately, God created the universe for his own glory.[30] All subsidiary purposes within the creation lead to this one. Thus God, expressing his own character, voluntarily and wilfully created the universe for his own glory.

In a human, such a motive would be hubris, but this cannot be true for God. His glory is the ultimate glory; there can be no greater.

The universe "declares the glory of God" and was created for this purpose. God's glory is reflected both in its cosmology and in its biology. But is it reasonable to conclude that stochastically generated outcomes can be equivalent for this purpose? The distribution of matter in the early universe represents one stochastic outcome from a vast set of possibilities. Are they all purpose-equivalent? It seems reasonable to conclude that they are. Any one of them would have fulfilled God's purposes. Indeed, these fluctuations may be necessary to produce regions of matter at sufficient densities for the formation of galaxies, stars, and planets. And the wide range of densities provides for a rich and glorious diversity of such objects. But beyond this, no particular distribution of matter seems necessary. The actual outcome can be determined stochastically and still be consistent with God's purposes.

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In the biological world, it is difficult to think of the outcomes as being discrete. The species on our planet change with time and, because of genealogical continuity, blend into each other. The set of outcomes is vast though it is not limitless. Mutations are not directed toward any particular biological function, but only those that are compatible with the current physical and biological environment persist. A consequence of this is convergence, the tendency for unrelated species in similar ecological niches to develop similar functions and appearances.

Biological life on this planet has displayed a richness of diversity which, as with galaxies and stars, declares God's glory. His creativity is revealed by the multitude of species that have appeared over biological history. The contents of the outcome set have been designed by God. At any time, only a subset of species are compatible with the conditions on the planet. Matching compatible species with current conditions represents a local purpose. But this is continually being achieved. Species flourish over long periods except on those rare occasions when the rate of change is catastrophic. Even then, some life persists.

There would seem to be a flaw in this account. Are not humans, the image-bearing species, a single outcome that is necessary to fulfil God's purposes? How can we account for the achievement of this local purpose?

The probability of occurrence of a particular outcome during some period in the history of the universe depends on three things. These are the nature of the outcome, the resources that provide opportunities for the outcome to occur, and how God has chosen to act. In the case under consideration, possible outcomes range from humans appearing on Earth to an image-bearing species (us or others similar to us in key ways) appearing somewhere in the universe. God's image is not physical, and the whole universe is his creation. Resources include the number of planets favorable to life, the ease with which life can appear on such a planet, and the ease with which humans or something like us can appear given the presence of life. In our present state of ignorance, we cannot make definitive statements about any of these.

Finally, there is the question of how God has chosen to act in biological history. Among Christians who accept, possibly with minor modifications, the conventional evolutionary account, the required outcome has often tacitly been assumed to be the appearance of humans on Earth. To achieve this, God has been presumed to guide the evolutionary process in undetectable ways. However, if the goal is less restrictive, it may simply be inevitable given God's overall design of the creation and its processes. Paleobiologist Simon Conway Morris, for example, thinks that planets congenial to life may be extremely rare, and the appearance of life extremely difficult. But he concludes that once life has gotten started "the constraints of biological evolution and the ubiquity of convergence make the emergence of something like ourselves a near inevitability."[31] Whatever mechanism God used, this purpose has been achieved. We are here.

The congeniality of the universe for life has often been noted.[32] The values of a few physical constants, such as the gravitational constant and the fine structure constant that controls the strength of interactions between radiation and matter, are not fixed by quantum theory but must be determined experimentally. Yet they are fine tuned. Small changes in the value of any one of them would rule out the existence of life as we know it. The possible implications of this anthropic cosmological principle have generated considerable controversy and led to further research in which more than one constant is altered at a time. This research has shown that universes with stars or star-like objects can be produced with some other sets of values for the constants. Whether such universes are compatible with life remains conjectural.

These cosmological and biological processes are consistent with God's purposes. But how, in general, do stochastic processes with purpose-equivalent outcomes fit in with our understanding of God's actions?

## God's Actions

As well as creating the universe, God can be thought of as acting in it in two ways.[33] First, he achieves his general purposes by his uniform divine action in sustaining its orderly, coherent processes. Second, he achieves particular purposes through his special divine action. The latter includes anomalous actions that appear discontinuous with the more prevalent orderly processes of the creation. Such actions are often called "interventions" though this term makes it sound, incorrectly, as though God is not otherwise engaged in the workings of the universe.

In recent years, considerable thought has been given to possible means of special divine action that merge smoothly with the orderly processes of the creation. Two are of interest here. On the most minute level, God may act by determining some or all of the seemingly stochastic outcomes of quantum processes.[34] On another level, God may alter the outcomes of chaotic processes through minuscule perturbations.[35]

Where do processes whose outcomes are determined stochastically from a set of purpose-equivalent possibilities fit into this scheme? It seems quite reasonable to classify them as part of God's uniform divine action. Their existence does not exclude special actions, including anomalous ones, or other uniform actions of a deterministic type. But among the orderly processes of the universe, they have a unique feature. Because multiple outcomes are possible from stochastic processes, God's purposes are being achieved even while the exact course of events is underdetermined.

As a type of uniform divine action, stochastic processes with purpose-equivalent outcomes involve a tradeoff with God's use of quantum or chaotic processes for his special purposes. If God harnesses only some quantum outcomes for his specific purposes, the rest are stochastic, purpose-equivalent ones. Alternatively, if God determines every quantum outcome, there are none left to be purpose-equivalent. The situation for chaotic processes is parallel to that for quantum ones.

While we can propose ways that God might act, we cannot be definite about how he actually does. Such issues lie beyond the reach of our empirical methods. No argument has been given here to demonstrate that any process in the universe actually is stochastic though some apparently are. What has been shown is that if such processes do exist, they do not entail a lack of purpose. These processes were also created by God and serve his goals.

The error that many, including philosophers like Stamos and Rosenberg, make is in drawing their conclusions from the nature of these processes, their stochasticity, and hence their unpredictability. These conclusions reflect only local purposes. An accurate understanding can only be gained by studying the entire set of possible outcomes and the system of which the process is a part. Purposes which will be achieved by the system no matter which outcome occurs, are readily attainable. This does occur in systems of our own construction and can even be seen in mundane activities like sports. Such counter-examples refute the claims of those who are blind to the purposes of chance.

### Notes

[1]2 Samuel 1, King James Version. Many modern versions express the lack of intention without using the word "chance."

[2]Peter van Inwagen,"The Place of Chance in a World Sustained by God," in *Divine and Human Action: Essays in the Metaphysics of Theism*, ed. Thomas V. Morris (Ithaca, NY: Cornell University Press, 1988), 211–35.

[3]Jacques Monod, *Chance and Necessity: An Essay on the Natural Philosophy of Modern Biology,* trans. Austryn Wainhouse (New York: Vintage-Random, 1972).

[4]Early responses to Monod were given by theologian Arthur Peacocke in his 1978 Bampton Lectures and by statistician David Bartholomew in Arthur Peacocke, *Creation and the World of Science: The Re-Shaping of Belief* (Oxford: Oxford University Press, 2004); David J. Bartholomew, *God of Chance* (London: SCM, 1984). The latter is now available as an e-book at www.godofchance.com and has been

updated as David J. Bartholomew, *God, Chance and Purpose: Can God Have It Both Ways?* (Cambridge: Cambridge University Press, 2008). For references to other works on chance and theology, see Thomas W. Woolley, "Chance in the Theology of Leonard Hodgson," *PSCF* 58 (2006): 284–93.

[5]Daniel C. Dennett, *Darwin's Dangerous Idea: Evolution and the Meaning of Life* (New York: Simon and Shuster, 1995).

[6]David N. Stamos, "Quantum Indeterminacy and Evolutionary Biology," *Philosophy of Science* 68 (2001): 164–84; Alex Rosenberg, "Discussion Note: Indeterminism, Probability, and Randomness in Evolutionary Theory," *Philosophy of Science* 68 (2001): 536–44.

[7]Tamler Sommers and A. Rosenberg, "Darwin's Nihilistic Idea: Evolution and the Meaninglessness of Life," *Biology and Philosophy* 18 (2003): 653–68.

[8]William Feller, *An Introduction to Probability Theory and Its Applications* 1, 3d ed. (New York: John Wiley and Sons, 1968).

[9]Alain Aspect, "To Be or Not to Be Local," *Nature* 466 (2007): 866–7; Simon Gröblacher, T. Paterek, R. Kaltenbaek, C. Brukner, M. Zukowski, M. Aspelmeyer, and A. Zeilinger, "An Experimental Test of Nonlocal Realism," *Nature* 466 (2007): 871–5.

[10]Kathleen T. Alligood, T. D. Sauer, and J. A. Yorke, *Chaos: An Introduction to Dynamical Systems* (New York: Springer-Verlag, 1996); Robert L. Devaney, *An Introduction to Chaotic Dynamical Systems*, 2d ed. (Redwood City, CA: Addison-Wesley, 1989).

[11]John C. Polkinghorne, *Science and Providence: God's Interaction with the World* (1989; reprint, Philadelphia, PA: Templeton Foundation Press, 2005).

[12]For other human uses of chance, see Bartholomew, *God, Chance and Purpose.*

[13]Gary M. Mullet, "Simeon Poisson and the National Hockey League," *The American Statistician* 31 (1977): 8–12.

[14]This account is based on memories of a long-ago radio interview with a league official.

[15]Montreal Canadiens defeated Toronto St. Patricks, 14-7, Jan. 10, 1920; Edmonton Oilers defeated Chicago Black Hawks, 12-9, Dec. 11, 1985; "NHL Overall Team Records Most Goals, Both Teams, One Game" www.rauzulusstreet.com/hockey/nhlrecords/records8.html (accessed May 12, 2007).

[16]David R. Cox, *Planning of Experiments* (New York: John Wiley and Sons, 1958).

[17]Peter van Inwagen,"The Magnitude, Duration, and Distribution of Evil: A Theodicy," *Philosophical Topics* 16 (1988): 161–87; Report in *Philosophy of Religion: A Reader and Guide*, ed. William L. Craig (New Brunswick, NJ: Rutgers University Press, 2002), 370–93; Peter van Inwagen, *The Problem of Evil* (Oxford: Clarendon Press, 2006).

[18]van Inwagen, "The Place of Chance in a World Sustained by God."

[19]"Sloan Digital Sky Survey," www.sdss.org (accessed Aug. 24, 2008).

[20]Claude-André Faucher-Giguère, A. Lidz, and L. Hernquist, "Numerical Simulations Unravel the Cosmic Web," *Science* 319 (2008): 52–4; Rodrigo A. Ibata and G. F. Lewis, "The Cosmic Web in Our Own Backyard," *Science* 320 (2008): 50–2.

[21]Wayne Hu and S. Dodelson, "Cosmic Microwave Background Anisotropies," *Annual Review of Astronomy and Astrophysics* 40 (2002): 171–216. For more recent developments, see "Wilkinson Microwave Anisotropy Probe" map.gsfc.nasa.gov (accessed Nov. 29, 2008).

[22]For more details, see Graeme Findlay,"Human Evolution: How Random Process Fulfils Divine Purpose," *PSCF* 60 (2008): 103–14; Elizabeth Pennisi,"Breakthrough of the Year: Human Genetic Variation," *Science* 318 (2007): 1842–3.

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