# The Evolution of Reason

## Logic as a Branch of Biology

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# 1

# The Biology of Logic

In *The Descent of Man* Charles Darwin made some remarks about 'Reason.' They begin

> Of all the faculties of the human mind, it will, I presume, be admitted that *Reason* stands at the summit. Only a few persons now dispute that animals possess some power of reasoning. Animals may constantly be seen to pause, deliberate, and resolve. It is a significant fact, that the more the habits of any particular animal are studied by a naturalist, the more he attributes to reason and the less to unlearnt instincts. . . . (Darwin 1871, p. 75)

The passage continues with an astute commentary on the evolution of Reason in humans and animals.

The discussion initiated by Darwin has continued to this day. It has grown into a sophisticated discourse of considerable fascination, drawing on several disciplines. It has delved into animal reasoning in general and human rationality in particular. I have no special quarrel with the details of this extensive literature, to which I have contributed. Nevertheless, regarding the whole, I cannot help suspecting that something akin to a Ptolemaic blunder has been made. The larger order of things has been misconceived.

The original Ptolemaic blunder was rectified by the Copernican revolution, an event that has long intrigued methodologists of science. Ptolemy had the heavenly bodies orbiting a still earth. Centuries later, Copernicus changed the course of astronomy by taking the sun to be the central stillness instead. At the time there were no new observational findings to prompt the change. It was a matter of interpreting the same empirical data from a radically different standpoint. A number of subtle explanatory economies combined to support the

heliocentric model. The acceptance of the new theory was gradual, and was abetted by a contemporaneous questioning of Aristotelian doctrines (Kuhn 1957).

Today, in the general drift of scientific thought, *logic* is treated as though it were a central stillness. Although there is ambiguity in current attitudes, for the most part the laws of logic are still taken as fixed and absolute, much as they were for Aristotle. Contemporary theories of scientific methodology are logicocentric. Logic is seen commonly as an immutable, universal, metascientific framework for the sciences as for personal knowledge. Biological evolution is acknowledged, but is accorded only an ancillary role as a sort of biospheric police force whose duty it is to enforce the logical law among the recalcitrant. Logical obedience is rewarded and disobedience punished by natural selection, it is thought. All organisms with cognitive capacity had better comply with the universal laws of logic on pain of being selected against!

Comfortable as that mindset may be, I believe I am not alone in suspecting that it has things backward. There is a different, more biocentric, perspective to be considered. In the alternative scheme of things, logic is not the central stillness. The principles of reasoning are neither fixed, absolute, independent, nor elemental. If anything it is the evolutionary dynamic itself that is elemental. Evolution is not the law enforcer but the law giver – not so much a police force as a legislature. The laws of logic are not independent of biology but implicit in the very evolutionary processes that enforce them. The processes determine the laws.

If the latter understanding is correct, logical rules have no separate status of their own but are theoretical constructs of evolutionary biology. Logical theory ought then in some sense to be deducible entirely from biological considerations. The concept of a scientific *reduction* is helpful in expressing that thought. In the received methodological terminology the idea of interest can be articulated as the following hypothesis.

Reducibility Thesis: *Logic is reducible to evolutionary theory.*

This is intended to apply at least to the ordinary, classical theories of logic, in a standard sense of reducibility to be explained.

To paraphrase, the hypothesis is that the commonly accepted systems of logic are branches of evolutionary biology. The foundations of logical theory are biological. The principles of pure Reason, however pure an impression they may give, are in the final analysis propositions

about evolutionary processes. Rules of reason evolve out of evolutionary law and nothing else. Logic is a life science. That is, of course, only an impressionistic gloss of the thesis; its exact meaning will have to be clarified as we go along.

The thesis might on first encounter seem dubious or even absurd. Certainly it is in need of interpretation and qualification. Nevertheless I hope to demonstrate that it has a core of truth that is entirely defensible. It would be too much to hope to establish it with finality in any single work, but the reasons for thinking it plausible and attention-worthy can be set forth. I beg the reader's suspension of disbelief until the chain of reasoning that supports the thesis can be laid out.

The issues involved are not vacuous. The philosophy of logic is at stake and perhaps the practice too. If as students of logic we indulge indefinitely the ancient habit of regarding logical principles as absolute and independent of biology, we will never think to look to evolutionary theory for a better understanding of them, or for ways of validating or refining them. The time may be ripe to look more seriously in that direction. If logic really is a matter of evolutionary dynamics, it should be so addressed.

It is only in recent years that it has become feasible to analyze logic from the standpoint of an advanced theory of evolution. Evolutionary biology is still young as an exact science. Parts of it have matured sufficiently by now, though, so that their ties with the foundations of logic have begun to emerge. The relationship has yet to be articulated to everyone's satisfaction, but it is sensed. This essay is my attempt to bring the ties into clearer focus, so that others may judge more easily whether a change of outlook is called for.

## THE PROVENANCE OF LOGIC

Everyone will agree that something called Reason exists, is important, perhaps even "stands at the summit . . . of all the faculties of the human mind" just as Darwin said. It is also clear that this thing called Reason, whatever it may be, is based on principles called Laws of Logic. The puzzle is: *Where do the Laws of Logic come from?* That will be the topic question of our inquiry.

The answer to be proposed is that logical law comes directly from evolutionary law. That it does so is the intuitive content of the Reducibility Thesis. The hypothesis that logic is reducible to

evolutionary theory is a methodologically explicit way of saying, and providing a handhold for demonstrating, that logical principles follow in the train of laws of evolution.

In case the thesis still seems obscure, the spirit of it can be illustrated with a couple of hypothetical scientific questions and answers. The first question is, "How do birds manage to fly?" A full treatise on the subject would involve two different sorts of theory. One sort would have to do with the laws of aerodynamics – the physics of gases, the viscosity of air, slipstreams, loads, lift, and so forth. The aerodynamic theory would be needed to explain how the design of the wing succeeds. The other kind of theory would concern the evolutionary considerations that brought about the flight adaptation in birds and gave it its present form. It would take up how the selective forces associated with the advantages of flight acted on genetic variation to increase fitness in the population, causing the flight adaptation to appear and be refined. Topics such as population process models, measures of fitness, and evolutionary competition would be featured in this second part. Thus the answer as a whole would involve an interplay of at least two different sorts of principles, one the laws of aerodynamics and the other the laws of evolution.

The second question is, "How do humans manage to reason?" Since the form of this question is the same as that of the first, it would be natural to attack it in a similar two-pronged fashion. One part of the answer, which might naturally be placed at the beginning of a treatise on the question, would consist of logical theory. The different kinds of logic – deductive, inductive, mathematical, etc. – would be expounded and derived from first principles, perhaps in the form of axiomatizations of the various logical calculi. These ideal systems would be taken to define the rules of correct reasoning. The explanation of how humans evolved in ways that exploit these principles would come later on. The stages of adaptation to the rules of logic would be discussed, including some consideration of how well or poorly the human mind succeeds at implementing the fundamental logical principles set forth in the first part. Somewhere in the latter part there would be talk of selective forces acting on genetic variation, of fitness, of population models, etc. As with the former question, two distinct sorts of theory appear to be involved. There would again be two parts to the exposition, a first part explaining the laws of logic and a second the laws of evolution. All this seems, on the surface at least, in good analogy with the explanation of bird flight.

What the Reducibility Thesis proposes is that it is a *false* analogy. *There are no separable laws of logic*. It is tempting to think of the power of reasoning as an adaptation to separate principles of logic, just as flying is an adaptation to separate laws of aerodynamics. The temptation should be resisted. The laws of Reason should not be addressed independently of evolutionary theory, according to the thesis. Reasoning is different from all other adaptations in that the laws of logic are aspects of the laws of adaptation themselves. Nothing extra is needed to account for logic – only a drawing out of the consequences of known principles of natural selection.

It follows that the first part of the hypothetical treatise on how humans manage to reason – the pure logic – is superfluous. The second, evolutionary, part should suffice to tell what Reason is and where the principles of reasoning come from. The prolegomenon on logic can be omitted in favor of a unified treatment in which the laws of logic emerge naturally as corollaries of the evolutionary laws.

Moreover, if this *can* be done it *should* be done. At least, it should if one believes in Ockham's razor. It is a matter of explanatory economy, which is no less important here than it was for Copernican astronomy. If the reducibility hypothesis is correct, an explanation of reasoning need not import principles of logic from some alien venue as though they were a form of knowledge peculiar unto themselves. They are already fully implicit in known evolutionary principles, waiting there to be noticed and drawn out. The laws of logic are redundant in the presence of the laws of evolution.

Because it would be easy to mistake our purpose, I had better say what the purpose is not. The aim is *not* just to show that organismic reasoning ability is a product of evolutionary forces. That much is already obvious and it is hard to see how any Darwinian could deny it. The problem with such an assertion is not that it is untrue, but that it says nothing about where the laws of logic come from. It evades the topic question. It leaves the door open to the conventional conceit according to which evolutionary pressures mold the organism to preexistent, independent, logical principles descended somehow from some rational paradise. It is the latter presumption in its various guises that I wish to oppose. According to the Reducibility Thesis there is no such rational heaven. The laws of logic are neither preexistent nor independent. They owe their very existence to evolutionary processes, their source and provenance.

## THE CLASSICAL FAMILY OF LOGICS

Actually, the hypothetical treatise on how humans manage to reason is not so hypothetical. In the chapters to follow, the attempt will be made to explain organismic reasoning in a manner respectful of Ockham's razor. The aim is a unified treatment in which the laws of logic are not introduced by fiat, nor drawn from some separate philosophical foundation, but emerge inevitably from the laws of evolution themselves. Different kinds of logic will then appear as manifestations of evolutionary laws at different levels of abstraction.

*Deductive* logic is probably what most people first think of on hearing the word 'logic'. Deductive reasoning is the kind of logic that offers argument forms in which conclusions follow from premises with (alleged) certainty. But deductive logic, though renowned in the pantheon of rationality, is only one constituent of a greater whole. The larger logical complex involves other formalisms including general *mathematics*. Deductive logic and mathematics are so intertwined that it has seemed to many to be an arbitrary matter where one sets the dividing line between them. Looking in another direction, deductive logic is also closely tied to probabilistic or *inductive* logic, the deductive being a sort of limiting case of the inductive according to one view. Statistical reasoning then elaborates probabilistic induction. Going a step further, probabilistic logic is implicated in *decision theory*. In the theory of decision under uncertainty, sometimes also called the 'logic of decision', probability theory is enhanced by the introduction of values called 'utilities' to provide a way of reasoning about the most coherent course of action a rational agent might take.

Each of these interrelated areas of logical theory presents a facet of rationality. It is the whole complex of such systems that is referred to in the Reducibility Thesis under the cover term 'logic'. The hypothesis is that they are *all* reducible to evolutionary theory.

Attention will be confined here to the standard, or 'classical', systems of logic. They are the common theories of deduction, probability, decision, and mathematics usually presented in textbooks and elementary courses and typically applied in practice. They are the logics that most mathematicians have in mind when attempting to formalize a proof, what most statisticians regard as foundational, what consultants commonly use to analyze management decisions, what artificial intelligence researchers most often build into their programs, and so on.

There are of course other kinds of logic than the classical, but to keep the discussion within bounds they will not be considered here. The better-known nonclassical systems include intuitionistic logic, modal logic, combinatorial logic, tense logic, many-valued logic, fuzzy logic, relevance logics, and other more specialized types of formalized reasoning. Whether some of these nonstandard systems might also be reducible to evolutionary theory is an interesting and perhaps researchable question, but not one that will be addressed in these pages.

It will be seen later that evolutionary theory gives rise not only to the classical systems of logic, but also to some generalized versions of the classical calculi with nonclassical properties. The status of these unfamiliar logics will be a matter for discussion later. For the moment they are mentioned only as additional candidates for the reduction. In summary, the Reducibility Thesis as it will be taken up here asserts that all the above-mentioned classical systems of logic, and also certain associated paraclassical systems to be described, are reducible to evolutionary biology.

## BEHAVIOR AS COMMON GROUND

Decision theory is the branch of logic that comes into most immediate contact with the concerns of evolutionary biology. Decision theory and evolutionary theory are bound to each other by virtue of their mutual involvement with behavior. The concern with behavioral patterns provides a common boundary region between them.

The logic of decision is concerned with an agent's choice of the most reasonable course of action from a set of available courses of action. In decision theory a course of action is called an 'act', an 'option', or in complex cases a 'strategy'. But whatever it may be called, such a course of activity is a behavioral pattern of some sort. Now, behavior is something that evolutionary theory has much to say about. Behavior is observable, it is amenable to scientific prediction and explanation, and because it is a phenotypic property of organisms the possibility arises of explaining it in evolutionary terms. This makes behavior an interdisciplinary bridge approachable from both the biological and the logical sides.

The standard systems of logic – inductive logic, deductive logic, decision logic, and so on – are so tightly interwoven that the character of

the decision behavior posited in the decision-theoretic constituent of logic *determines* all of the remaining logic in the classical cluster. This may not be immediately apparent but will become clearer later. The upshot is that all of classical logic is closely tied to evolutionary theory and dependent upon it. If evolutionary considerations control the relevant aspects of decision behavior, and these determine in turn the rest of the machinery of logic, one can begin to discern the implicative chain that makes the Reducibility Thesis thinkable.

The general idea behind the reduction then is that evolutionary factors influence the character of reasoned behavior to the point of dictating it completely. Behavior is the fulcrum over which the evolutionary forces extend their leverage into the realm of logic. Viewed through the lens of biology, the behavior in question is evolutionarily fit behavior. Through the lens of logic it is rational decision behavior.

If the evolutionary control over the logic is indeed so total as to constrain it entirely, there is no need to perpetuate the fiction that the logic has a life of its own. It is tributary to the larger evolutionary mechanism. That being so, logic might as well be recognized outright as the branch of evolutionary theory that it is – momentous, but a branch nonetheless.

## POPULATION PROCESSES INDUCE LOGICS

By *biology* we shall usually mean evolutionary biology. Within evolutionary biology the narrower focus will be on *population biology*, widely considered to be the mathematical core of evolutionary biology. Population biology includes the formal study of population process models, population genetics, selection, adaptation, and evolutionary fitness. The reducibility hypothesis could have been reworded to assert that logic is reducible to population biology.

The interplay between logic and biology comes down to this. Theories of population biology, when made precise, take the form of mathematical population process models and the properties deducible from them. One of their deducible properties, it will be seen, is that they spawn rules of logic. That is, particular population theories entail not just a tendency on the part of fit population members to obey external logical constraints, but the logical rules themselves. The population models determine what fit behavior shall be, under the conditions

postulated; and this fit behavior, regarded as decision behavior, determines the logic.

In this way the general evolutionary tendency to optimize fitness turns out to imply, in and of itself, a tendency for organisms to be rational. Once this is shown there is no need to look for the source of logical principles elsewhere, for the logical behavior is shaped directly by the evolutionary forces acting on their own behalf. Because the biological processes expressed in the population models wholly entail the logical rules, and are sufficient to predict and explain rational behavior, no separate account of logic is needed.

## DEFINING REDUCTION

To say that logic is a 'branch' of biology, or that biology and logic are candidates for a 'unification', or that population processes 'induce' systems of logic, and so forth, is to speak loosely of a relationship that can be described more precisely as a *reduction.* Reduction has an honored place in science. It has been described as "the explanation or replacement of one scientific theory or branch of science by another" (Schaffner 1977, 146). It involves the grafting of one theory onto another in such a manner that the composite result is more economical of concepts and laws than the sum of the two original theories.

Historic examples of reducibility relationships include Newton's reduction of Kepler's planetary equations to the general laws of motion and universal gravitation, the reduction of Galilean mechanics to the same, the reduction of thermodynamics to statistical mechanics, and the reduction of parts of chemistry to particle physics. Mendelian genetics, or extensions of it, are thought by some to be largely reducible to molecular genetics. Methodologists still debate the details of these famous reductions, but few doubt that they are indeed scientific reductions in some sense or to some extent. In their time, all were first-class "Aha!" experiences.

The kind of reduction that will be relevant here is epistemological or nomological reducibility, or what is sometimes called *theory-reduction*. The general idea of a theory-reduction is that one theory is reducible to another just in case it can be derived from it by logical or mathematical steps without introduction of fresh subject matter. The simplest explicit characterization of theory-reducibility is the well-known model due to Nagel (1961) and others. Omitting some

refinements, a scientific theory $T_2$ is said in the Nagel model to be *reducible* to another theory $T_1$ if and only if (1) the concepts of $T_2$ can be defined in terms of concepts of $T_1$, and (2) using these definitions, the propositions of $T_2$ can be deduced from the propositions of $T_1$. Clauses (1) and (2) are the so-called conditions of *connectability* and *derivability*.

It is understood that the two operations can proceed in any number of stages. New concepts can be defined within the reducing theory, then new propositions can be derived with the help of the concepts just defined, then more new concepts can be defined with the help of the newly derived theory, and so forth until the theory to be reduced is eventually arrived at. Theory-reduction is a matter of derivability in any number of stages with allowance made for creativity of definition.

The formal Nagel definition is an oversimplification of what many actual theory-reductions are like. Some believe it to be a gross, even hopeless, oversimplification (Burian 1985, 25; Schaffner 1977). But it is adequate for simple cases and conveys the spirit of more involved reductions. Generalizations of it have been proposed and they may indeed appropriately broaden the scope of the original (Schaffner 1993). However, as it applies to the Reducibility Thesis, the modifications and extensions to the Nagel model that are needed are probably minimal. It would be premature to go into the exact formal details of the kind of theory-reduction required. Nagel's original characterization comes close enough to what is wanted for purposes of preliminary exploration.

The reduction of interest should not be confused with another kind of reduction to which it bears only a distant resemblance. There is a commonplace form of reductionism encountered in biology and ecology in which the properties of a biological system are analyzed hierarchically in terms of the properties of the system's members, physical components, or ecological subsystems. It is the type of reducibility referred to by G. C. Williams (1985) when he wrote "Reductionism is the seeking of explanations for complex systems entirely in what is known of their component parts and processes." The reduction of concern here is not of this mechanical kind. Although it may be possible to cast the sorts of reductions Williams refers to in the Nagel form, not all Nagel reductions are based on physical componential analysis. The theory-reduction of present interest has little to do with physical part–whole relationships and much to do with derivation and definition.

In comparing biology with logic, one has population process models on the one hand and systems of logic on the other. Both can (ideally) be cast in exact mathematical terms. The nub of the reducibility claim is that from each population model regarded as a formal biological theory one can derive, using the mathematics of fitness optimization, an associated theory of logic. In so doing, one establishes logical principles on the basis of evolutionary precepts. The logical principles so derived are local to the particular population model, but – or so it will be argued – no less logical for that.

We shall not be able to establish the reducibility claim definitively here by producing complete derivations of logical systems from population models in full mathematical detail. The Nagel model assumes that in principle the reduced and reducing theories can be formalized explicitly and completely, ideally in axiomatic form, and that the reduction supplies a complete formal deduction of the reduced theory from the reducing with every tiniest deductive step in order. However, Nagel recognized and explicitly stated that this is an "ideal demand" not usually satisfied in the normal course of scientific reductions. More often a reduction is largely conceptual with exact derivations given only for certain critical portions of the chain of reductive reasoning. That is the precedent to be followed here. Formal definitions will be offered and relevant theorems stated that are proved either here or by other authors. With some informal reasoning to connect them, these will come together to constitute an argument for reducibility.

Reductionism has had its critics, especially in biology; and the critics are able to point to abuses. The criticisms have to be taken seriously. It should be remembered, though, that it is the abuses that are blameworthy, not the reductive method itself.

## REDUCTIONISM IN LOGIC

In the common Darwinian view, all human and animal capabilities, including mental capacities, are biologically evolved. Logical reductionism agrees but goes beyond that obvious point. The additional claim it makes is that there is a direct dependency of the laws of logic on the laws of evolution – a sort of homomorphism from evolutionary theory to logical theory. The evolutionary laws extend across the boundary of behavior to control the logic.

If the claims of evolutionary reductionism can be sustained, logical laws are not just products of historic evolutionary processes, but are themselves formulable as part of the theory of those processes. Not only do laws of logic evolve, they are also partial descriptions of what it means to evolve. A logical schema becomes a kind of evolutionary equation or proposition, albeit heavily disguised.

If this be the case, evolutionary biology is unique among the sciences as the seed bed for the laws of logic. If the various sciences are likened to factories of knowledge – factories that use logical tools – then population biology is the tool factory. Biology is an ordinary science but its evolutionary branch is a subscience that, in addition to its more ordinary offices, predicts and explains logic.

According to the reductionist claim, logic is so biological that if the classical laws of logic had not already been worked out independently, an evolutionist innocent of any prior knowledge of formal logic could in principle have stumbled upon them simply by drawing out the consequences of standard evolutionary models and processes. Starting in the next chapter we will put ourselves in the position of such a logically naive evolutionist in order to witness the extent to which the drawing-out can actually be accomplished.

## LOGIC AS SCIENTIFIC GENERALIZATION

In the usual view, the laws of logic are independent truths to which organisms must adapt. Complex animals are considered to have evolved in such a way as to implement to some extent these preexisting rules of reason. The more cognitively advanced the organism, the better the implementation, it is thought.

This 'implementation' is considered to take place through the evolution of neural mechanisms or other physiological means, but in any case, the process of adaptation to the rules has customarily been regarded as something distinct from the rules themselves. In maintaining that distinction, Nature is cast as an engineer who designs a computer to implement independently valid logical and arithmetic truths. The engineer designs the computer but not the truths. It is conceded that Nature does her designing differently from a human engineer, by an eons-long process of genetic trial and error in fact, but still the logical constraints are considered to be already set forth independently of anything Nature-as-designer

may do. Evolution has to accommodate itself to the logical boundary conditions.

The reductionist way of thinking calls this paradigm into question. In the reductionist view the evolution of rationality is not at all a matter of organismic brains 'implementing' preexisting logical rules or 'adapting to' them. Instead, it is a matter of rules of logic coming into existence as concomitants of the adaptive process itself. Nature may be an engineer, but she is not the kind of engineer who works to implement preconceived design goals. Rather, this engineer engineers blindly and madly, without prior task specifications, and whatever gets engineered gets engineered. If rational organisms evolve, then the properties that prompt us to call them rational must have come out of the engineering procedure itself. They could hardly have come out of independent design requirements that Nature felt obliged to impose out of mysterious metaphysical loyalties.

Older tradition has it that rules of logic have a sovereign, transcendental validity that is in no way dependent upon any particular empirical science. Admitting that it is generally fit to reason correctly, the conventional view concludes that evolutionary pressures cause the behavior of sufficiently complex organisms to manifest an approximation to these rules. What is wrong with this, from the reductionist perspective, is the subtle assumption that the evolving ratiocinatory powers conform to logical constraints that are *extrabiological*. This unwarranted notion has falsely endowed logic with its own private criteria of validity, as though it were a law unto itself.

In the reductionist perspective, logic is not extrabiological but wholly emergent from evolutionary processes. There is no crisp category distinction to be made between logical and biological truths. There is no such thing as 'pure logic', if what is meant by that is a logic independent of empirical facts and physical processes. To the contrary, all logic is thoroughly impure and biologically contaminated from the outset.

## HINTS FROM THE LITERATURE

An evolutionary outlook on logic and rationality has been adopted by many writers, and many of the ideas to be dealt with here have been around a good while. As far as I am aware, I am the first author who has been rash enough to have suggested in print that logic is reducible

to evolutionary theory (Cooper 1987, 1988). Others have come to the brink however. Intimations of the biological character of logic are to be found scattered throughout the literature of several disciplines. Though a comprehensive survey of individual works would be too vast to contemplate, a few areas of inquiry can be pointed out as especially germane.

First there is the literature on evolutionary biology itself. Especially relevant are the parts that involve game theory and decision theory. Outside of biology, game theory is intended to formalize what is involved in acting reasonably in interactive choice situations, the idea being to capture an aspect of rationality in mathematical terms. Within biology (e.g., Maynard Smith 1982; Maynard Smith and Price 1973) game theory is given the additional twist that it is used to describe something that evolves. In the evolutionary context it is clear that game theory is not purely *a priori* but also empirical and biological, for the precise form of a game-theoretic logic is clearly dependent upon the relevant biological circumstances. (For surveys see e.g., Maynard Smith [1978, 1982] and Reichert and Hammerstein [1983]).

Decision theory is an elementary form of game theory. Works on game theory frequently present decision logic as a special case of game theory, namely, the case in which the player's 'opponent' happens to be a neutral Nature. Decision- and game-theoretic vocabulary was introduced into the evolutionary literature by Lewontin (1961). Explicit correspondences between decision-theoretic and evolutionary concepts have been listed and discussed, for example, by Templeton and Rothman (1974). When the decision-theoretic elements of evolutionary analysis were analyzed in greater detail and compared with those of classical decision theory, the idea of a 'natural decision theory' emerged (Cooper 1981). Natural decision theory was conceived as the evolutionary analog of standard decision theory, the difference being that in natural decision theory the role of decision maker is played by natural selection. Later contributions have used decision-theoretic formalisms in the evolutionary context in various ways. A paper provocatively entitled "Darwin Meets the Logic of Decision" (Skyrms 1994) and other works by the same author analyze the formal analogies – along with some disanalogies – between evolutionary dynamics and standard theories of decision and games (Skyrms 1996, 1997).

Decision theory is intimately related to probability theory. A famous treatment blending the two is contained in a book by Savage (1972), a remarkable work that extracts subjective probability theory from an

austere behavioral basis. Savage's system is an embodiment of the important idea that probabilistic induction rests on decision- and utility-theoretic foundations. In present terms it is essentially reducible to them. There is, as yet, no significant literature on evolutionary probability theory as there is on evolutionary game and decision theory, but such a subject suggests itself because of the reductive connections between decision theory and inductive logic worked out by Savage and others.

Probability theory, the formal basis of statistical inference, is in turn intimately related to deductive logic. The connection has been formalized in various ways. One account has it that the classical deductive logic is the special case of inductive logic in which attention has been confined to inferences in which the conclusion may be reached with a probability approaching certainty. More elaborate analyses of the relationship include the one provided by Carnap and Jeffrey (1971).

According to a philosophical school known as Logicism founded by Gottlob Frege, Bertrand Russell, and Alfred North Whitehead, general mathematics is reducible to deductive logic. Much has been written both for and against this position. The discussion becomes relevant here if logic can itself be shown to have biological foundations. If it does and if logicism is accepted, then mathematics must have biological foundations too.

Still other disciplines bear on the reducibility thesis. In the economics literature, many a study is inhabited by an idealized creature called 'rational man' or 'economic man'. The penchant for analyzing rational economic behavior has led to fundamental contributions to logic, especially the already-mentioned logic of decision and utility theory and game theory, the latter having received much of its initial impetus in economics (von Neumann and Morgenstern 1953). Economic papers have occasionally appeared that interpret the notion of economic or decision-theoretic utility explicitly in terms of evolutionary fitness (e.g., Robson 1996). Pockets of the economic literature on decision and game theory resonate with evolutionary overtones for those so attuned.

There is a voluminous psychological literature about logic and decision making as actually practiced by humans and animals. Points of contact with evolutionary theory are frequently discussed. The literature contains a body of experimental work comparing actual human and animal reasoning with the reasoning predicted by classical and other systems of logic. There are findings of systematic divergences

between classical and actual reasoning and these have been the subject of much speculation. Doubtless many of the observed discrepancies signify nothing more than slips or blunders, but in some cases the experimental subjects are not only consistent with one another in their deviant responses but stoutly refuse to change their responses even after having had the "correct" classical reasoning explained to them.

In such circumstances the possibility exists that the subjects are using a biologically valid system of logic that simply happens to differ from classical norms. These anomalies are grist for the mill of biological reducibility. Under the hypothesis of reducibility, some of the nonclassical elements of the systems of logic used by humans could well be explainable on the basis of more realistic population process models than the ones that give rise to the classical logic. The observed nonclassical reasoning might sometimes be predictably fitter, evolutionarily, than standard logical reasoning.

Philosophers of biology have provided thought-provoking discussions of the phenomenon of rationality, and their discussions constitute the setting for the present study (e.g., Sober 1981). They concern an aspect of what has come to be known as *evolutionary epistemology*, the philosophy of knowledge considered in the light of evolutionary theory. The paper by Campbell (1974) has been seminal, and Ruse (1986a, 1989) comments directly on the evolutionary epistemology of organismic reasoning. Much of what has been said by contributors to this literature reinforce the viewpoint that reasonableness is relative to evolutionary circumstances.

Konrad Lorenz, considered a founding figure of evolutionary epistemology, wrote (1941):

> Kant's statement that the laws of pure reason have absolute validity, nay, that every imaginable rational being, even if it were an angel, must obey the same laws of thought, appears as an anthropocentric presumption. . . . Nothing that our brain can think has absolute, *a priori* validity in the true sense of the word, not even mathematics with all its laws.

Such denials of an absolute *a priori*, and explicit recognition of the biological relativity of logic and even mathematics, presage reductionist systems such as the one to be developed here. Authors such as Lorenz have anticipated our theme, though it remains to be shown in reductionist terms just why they are right.

The relationships among these various theories have been the subject of investigations by evolutionists, statisticians, economists,

logicians, metamathematicians, and philosophers of the highest competency and reputation. In some cases the connections have been formalized rigorously, with results proved as theorems to the most exacting standards. The chief obstacle to comprehending the evolutionary character of logic therefore lies not so much in the lack of foundational work on any given discipline, nor even in the various interdisciplinary links taken pairwise, but rather in the general fragmentation of the different studies. Each has been carried out in isolation using a local vocabulary, creating the illusion of bounded disciplinary regions. But if the time has arrived to contemplate a broader unification, it is at least encouraging that the pieces of the puzzle have already been examined separately with great care. It remains only to fit them together.

## SUMMARY

From antiquity, various philosophies of logic have been proposed to explain the origin and character of rational thought. Some have given rise to elegant formal symbolic systems that allegedly codify precise logical principles, most prominently the various classical logical calculi. The foundations of the systems have been laid on motivating ideas ranging from faith in a rational intuition to theories of truth and semantics. Without necessarily discarding any of these considerations as irrelevant, we have suggested that there may be a more comprehensive approach to the foundations of logic in which logic is developed as a subscience of evolutionary theory.

Such a development is feasible if it can be shown that the principles of logic can be derived directly from evolutionary propositions. That this is possible is a hypothesis called here the Reducibility Thesis. It states that the laws of logic, or at least of classical logic and certain generalizations of it, are reducible to evolutionary biology in a standard sense: The terms of the logical theory are definable in evolutionary terms and logical assertions are deducible from evolutionary assertions.

If the Reducibility Thesis has merit, the principles of rationality are so deeply embedded in evolutionary theory that their foundations cannot rigorously be investigated independently of it. The motive for seeking these deeper foundations is not just that the capacity to reason is produced by evolutionary processes, a fact now well accepted by the

modern mind. It is that the underlying rules of reasoning are themselves recodifications of the properties of the processes.

The reductionist claim will be regarded with deep skepticism by many. It has long been customary to set forth systems of logic as though they were independent of any particular empirical science. Traditionalists might for that reason think it perverse to bestow on evolutionary science any special formative status with respect to logic. Indeed, to scholars unfamiliar with the associations between logic and evolutionary theory, the very thought of logic as a department of biology must seem bizarre. But those who are inclined to reject the idea out of hand should be asked, before passing judgment, to examine the chain of biological steps leading from the evolutionary premises to the logical theory.