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REDUCTIONISM AND FUNCTIONAL EXPLANATION IN MOLECULAR BIOLOGY[1]

1. INTRODUCTION

Philosophical discussions of the issue of reductionism in molecular biology have routinely been remarkably confused over the use of the connected terms "reduction" and "reductionism"[2]. For example, the main defender of the relevance of reductionism in molecular biology, Schaffner, has argued that though molecular biologists are not actively carrying out reductions, the result of their activities is a reduction of parts of biology to physics and chemistry (Schaffner 1974). Meanwhile, Wimsatt (1976) has defended the position that what molecular biologists are doing constitutes "reductions", but his explication of that notion has virtually no similarity to that of Shaffner. Further, the main critic of the relevance of reductionism in molecular biology, Hull, has argued that though what occurs in biology is not reduction in Schaffner's sense, there might be an "informal" sense in which reduction occurs (Hull 1976). At one point, Ruse (1971) even provided what amounts to a partial explication of a notion of "informal reduction" which was to be contrasted, presumably, with "formal reduction" which, he then claimed, was not occurring in molecular biology.

The roots of this confusion lie in the common failure to maintain two sets of distinctions that are quite critical to any clear analysis of the issues involved. The *first* of these consists of a quite simple distinction and is much less often missed than the second. This distinction is that between "reductionism" used to describe actual scientific practice (the research strategies of the scientists involved), and "reductionism" used to describe the structure of explanations

[1] Thanks are due to W. Wimsatt, K. Schaffner, and R. McClamrock for their comments on an earlier versions of this paper.
[2] The two distinctions that have been relatively clear on the use of these terms are of Wimsatt (1976) and Schaffner (1974). However, even they do not fully lay out the sets of distinctions proposed here and elaborated in Sarkar (1989).

afforded by molecular biology. Once this distinction is admitted, Schaffner's position, for example, becomes clear: "reductionism cannot be used to describe the former situation, but can be used to describe the latter"[3]. Almost all critics of reductionism in molecular biology from Ruse (1971) and Hull (1972) to Kitcher (1984) do not clearly maintain this distinction perhaps because they want to argue against the role of reductionism in either context. However, this failure leads to a serious misunderstanding of the history of molecular biology, as will be indicated below.

The *second* set of distinctions arises from the various construals that have been given to "reduction" in either of the two contexts separated above. Some have construed "reduction" as a relation between theories (Schaffner 1967, 1976; Hull 1972; Balzer and Dawe 1985, 1986, etc.) while sometimes offering radically different explications of that relation. Schaffner (1967), for example, construes "reduction" as the existence of a deductive relation between two theories, codified in first-order logic, whose entity and predicate terms have been appropriately connected using synthetic identities. The theory that is so deduced, the "reduced theory", is the biological one; the theory used to carry out the deduction, the "reducing theory" is the physical or chemical one. Balzer and Dawe (1985), however, adopt the method of reconstructing theories using informal set-theoric predicates advocated by Sneed (1971) and construe "reduction" as the existence of a certain relation between prospective *models* of these theories. However, others such as Wimsatt (1976) prefer not to construe "reduction" as a relation between some observed biological behavior and the physical or chemical mechanisms used to explain its occurrence. A similar construal is implicit in Kauffman (1972). Finally, Rosenberg (1978, 1985) has argued that all that is enveloped in the reduction of the behavior of biological organisms to physics and chemistry is their "supervenience" on the latter: there can be no alteration of biological behavior without a corresponding alteration of physical and chemical behavior of the entities involved. However the use of the latter behavior to explain the former is precluded because of the complexities involved.

The distinctions implicit in these conflicting construals of "reductionism" are best captured using an insight due to Mayr (1982). Mayr distinguishes between three broad categories of reductionism: *constitutive reductionism*, *explanatory reductionism*, and *theory reductionism* (1982, p. 59-63). Once these categories are distinguished, the various notions and explications of "reduction" can then be organized into these categories though Mayr does not carry out his additional step of clarification. The category of constitutive reduc-

[3] This distinction is, in fact, implicitly made, and consistently used, by Schaffner (1974).

tionism simply consists of those explications or notions of reduction that require that all biological processes occur in such a way that they are consistent with physical law. In effect, all that this category excludes is any vestige of vitalism. The category of explanatory reductionism includes those explications or notions of reduction that require that biological processes are explained by underlying physical and chemical ones[4]. Finally, the category of theory reductionism includes those explications or notions of reduction that necessarily construe it as a relation between theories. If this relation involves explanation, as it almost always does, then this category can be taken to be even more restrictive, or "stronger", than the category of explanatory reductionism[5]. Notions or explications of reduction falling into any of these categories can potentially be used either to investigate the research strategies pursued in molecular biology or to examine the structure of explanations afforded by it. Thus the two sets of distinctions are independent of each other.

For the sake of convenience, in the following discussion, a notion or explication of reduction will be said to fall into the category of constitutive reductionism if it falls into this category and no other; to fall into the category of explanatory reductionism if it falls into that category but not into the category of theory reductionism; and to fall into the last category simply when it does so. Thus Rosenberg's notion of reduction by supervenience (1978, 1985) falls into the category of constitutive reductionism. The explications of Wimsatt (1976) and Kauffman (1972) both fall into the category of explanatory reductionism. Schaffner (1967) and Balzer and Dawe (1985, 1986) have provided radically different explications of reduction that fall into the category of theory reductionism.

A failure to maintain both sets of distinctions has led to a lack of appreciation of the complexity of the role of reductionism in the history of molecular biology. If the first distinction is admitted, the question whether the research strategies of molecular biology were reductionist is independent of whether the structure of explanations in it are reductionist simply because research strategies can fail. Schaffner (1974), who implicitly and consistently maintains

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[4] It might appear that the category of explanatory reductionism is more restrictive than the category of constitutive reductionism. However, such a claim involves an additional ontological commitment that the biological entity whose behavior is being explained and the physical and chemical systems whose properties are being used for the purpose of the explanation are the same "thing". While this might very well be true, it is not necessary to make this commitment for the sake of the arguments in this paper. It will, therefore, be avoided.

[5] The qualification, "almost always", is made because in the case of at least one explication of reduction that falls under the category of theory reductionism, namely that of Balzer and Dawe (1985, 1986), it is not completely clear that explanation is involved.

this distinction, has argued that the research strategies in molecular biology are not reductionist but the resulting explanations are. However, Schaffner works only in the context of his own explication of reduction, ignoring the second set of distinctions introduced above. Thus, it is quite possible that whereas even if all explications of reduction falling under the category of theory reductionism fail to capture the research strategies followed by molecular biologists, some explication from the category of explanatory reduction might successfully do so. It turns out that, for some quite significant developments in the history of molecular biology, not even any explication of reduction falling in the category of explanatory reductionism can capture the research strategies involved (Sarkar 1989). One well-known example is that part of phage research that was guided by Delbrück and motivated by his search for complementarity in biological phenomena (Sarkar 1989, p. 90-167). The aim of this research was to discover biological phenomena that could not be explained by ordinary physics and chemistry but would require some "complementary" explanation[6]. Another less-known example is constituted by the theoretical attempts to decipher the genetic code in the 1950's which were guided by assumptions about the efficient storage and transmission of information far removed from physical or chemical considerations (Sarkar 1989). The results of these analyses, for either category of theory or explanatory reductionism, question the importance of reductionism in the research strategies historically followed by molecular biology.

However, both these research strategies were failures. Molecular biology is yet to come up with any phenomenon that cannot be explained by ordinary physics and chemistry, at least at the level to which data are available. Further, the actual decipherment of the genetic code in the early 1960's showed the naïveté of the theorical attempts of the 1950's. This raises the possibility that the structure of explanations afforded by molecular biology is still reductionist according to some explication or notion of reductionism. This possibility is enhanced by the observation that research in molecular biology continues to be quite successful in providing physical and chemical explanations of biological phenomena.

The exploration of this possibility becomes interesting because, once the second set of distinctions introduced above is carefully maintained, a curious fact about past philosophical discussions of reductionism in molecular biology emerges. There has been considerable criticism of the point of view that the structure of explanations in molecular biology is reductionist (Hull 1972, 1976;

[6] This was the aspect of the history of molecular biology that was emphasized, perhaps too much, by Stent (1966, 1968).

Ruse 1971; Kitcher 1984). Yet, with the exception of Rosenberg (1978, 1985), all these past criticisms have only considered explications of reduction falling within the category of theory reductionism. The most influential criticisms have been due to Hull (1972) and Kitcher (1984). Hull considers the relation between classical and molecular genetics and, in the context of the explication of reduction offered by Schaffner (1967), essentially points out that molecular biology provides explanatory mechanisms and not a reducing theory of the kind that Schaffner's explications requires. Kitcher discusses the same case and, unlike Hull, fails to find an adequate theory of classical genetics that would be a candidate for reduction[7]. Both of these arguments rely on one common objection: the absence of appropriate theories. At most these arguments can be extended to all explications of reduction that fall within the category of theory reductionism. They leave explications of reduction falling in the category of explanatory reductionism untouched.

Rosenberg (1985), by arguing for the supervenience of biological interactions on physical or chemical ones, does deny the possibility of any explication of reduction from the category of explanatory reductionism capturing the structure of explanations in molecular biology. The source of this argument is complexity. Since the same, or at least very similar, biological entities can have a very wide variety of physical or chemical constitutions, any attempt to explain their properties at the physical or chemical level would be incredibly complex. However, incredible complexity does not entail impossibility. More importantly, Rosenberg's argument goes against the justifiable intuition that every day molecular biology is providing more and more examples of physical and chemical explanations of biological phenomena. Thus, this argument does not detract much from the possibility that there is some explication of reduction from the category of explanatory reductionism that captures the structure of explanations in molecular biology.

However, the thesis maintained in this paper is that there exists a class of explanations in molecular biology, namely, functional explanations, whose structure cannot be captured by any model of reduction that falls into the category of explanatory reductionism, let alone theory reductionism. If this thesis is true, it presents a more significant problem to the program of construing explanations in molecular biology as reductionist than the previous objections of Hull and Kitcher which only bring into question explications of reduction from the category of theory reductionism. However, the effect of this thesis on that program is diluted because (i) the scope of such explanations in

[7] The explication of reduction that Kitcher actually considers is due to Nagel (1961) which is a degenerate case of Schaffner's.

molecular biology is quite limited and (ii) even at the present state of knowledge, it appears possible that such explanations might soon be captured by some explication of reduction from the category of explanatory reductionism. None of these points seem to have been previously noticed in the literature.

Section 2 begins with a discussion of an example of functional explanation in molecular biology that was introduced by Rosenberg (1985) who, however, failed to appreciate its full significance probably because of a failure to maintain the second set of distinctions introduced above. An explication of functional explanation due to Wimsatt (1972) is then adopted and this delegates to the theory of natural selection a critical role in ensuring the causal adequacy of such explanations. Since the theory of natural selection cannot be explained yet in physical or chemical terms, the structure of functional explanations cannot be captured by any explication of reduction from the categories of explanatory and theory reductionism. In Section 3 it is argued, however, that functional explanations only occur in molecular biology as answers to questions of origin and often provide only partial answers to these questions. Thus the relevance of the considerations adduced in Section 2 to the program of construing explanations in molecular biology as reductionist is severely limited. In Section 4 it is shown that, using some of the work done by Eigen and co-workers (Küppers 1975) in a different context, it might be possible to construct a purely physical theory of natural selection at the molecular level which is the level at which functional explanations in molecular biology occur. Thus some of these functional explanations might be captured by an explication of reduction from the category of explanatory reductionism. Details of this part of the analysis appear in Sarkar (1988).

2. FUNCTIONAL EXPLANATION, NATURAL SELECTION AND EXPLANATORY REDUCTIONISM

The use of functional explanations in molecular biology is very well illustrated by the following example originally invoked by Rosenberg (1985, p. 38-43). The genetic material in all living organisms, except some viruses, is DNA which consist of chains of four types of nucleotide bases, namely adenine (A), cytosine (C), guanine (G), and thymine (T). The order in which these bases appear in a DNA chain determines what sequence (if any) of amino acid residues in the polypeptide chain that DNA chain codes for. The process of producing a polypeptide chain from a DNA chain begins with a process called "transcription" during which the order of the nucleotides in the DNA chain is transcribed to a corresponding chain of RNA. For three of the four base types, the last-mentioned process takes place by the use of the standard base pairing scheme that occurs between complementary strands of DNA: the

C, G and T in the DNA corresponds to a G, C, and A in the RNA respectively. However, the A in the DNA does not correspond to a T in the RNA (as it would in a complementary strand of DNA), but to a new type of base, uracil (U). In other words, thymine does not occur in RNA at all, and wherever it might have been expected to occur by base pairing from its source DNA, uracil occurs in its place.

The question that now arises is that of the source of this difference between DNA and RNA. After all, the substitution of uracil for thymine does not alter any of the coding properties of the nucleic acids: there are still four types of bases, and three nucleotides code for each amino acid residue. Therefore RNA with uracil instead of thymine would have the same coding property as it would have had if thymine occurred in it. Further, the difference in structure between thymine and uracil appears to be small. This similarity of structure ensures that were uracil present in DNA instead of thymine, the DNA double helix structure could still be formed by the same base pairing mechanism that normally exists. In other words, DNA with uracil instead of thymine would continue to possess two of its most biologically significant properties, namely, that of coding for the amino acid residues in polipeptide chains, and that of maintaining the stable structure of the DNA double helix[8]. Yet there is this difference between DNA and RNA. Furthermore, in all biological organisms, thymine is basically synthesized from uracil. The reaction is endothermic and, therefore, energetically expensive for the organism. While this last fact could potentially be used to explain the occurrence of uracil in RNA out of thermodynamic considerations, it makes it even more difficult to explain the occurrence of thymine in DNA.

The provisional explanation of the occurrence of thymine in DNA instead of uracil is actually a little complicated. Cytosine, one of the nucleotide base types in DNA, can easily convert to uracil by deamination. Such deamination, when it occurs, destroys the coding property of a strand of DNA since it introduces a nucleotide base type, uracil, which is not normally present in DNA. However, such a situation cannot usually occur since there are present in the cell a set of enzymes which, through a complicated process, remove uracil from a strand of DNA and replace it with cytosine. Now suppose that uracil were a normal component of DNA. Then the deamination of cytosine would

[8] Of course, there can be some question whether the latter property should be considered particularly biologically significant. It might be held that some other structure could be just as efficacious. However, the double helix has some very useful properties that help maintain a stable structure. In particular, the helix provides a hollow cylindrical central core, protected from water, in which the hydrophobic purine and pyrimidine nucleotide bases are stacked.

not introduce into a strand of DNA a type of nucleotide base that did not normally occur in it. Then the sort of repair mechanism that excises uracil from DNA and replaces it with cytosine would be ineffective: it would end up excising a normal component of DNA. Further, if no such repair mechanism existed, the DNA would be extremely susceptible to having its coding property altered to that of a different strand of DNA by the deamination of cytosine assuming, of course, that a cytosine → uracil mutation would not always be silent[9]. Hence, the system as it exist now, including the incorporation of thymine rather than uracil in DNA, results in a greater stability of the code represented in that strand of DNA than what would have been obtained if uracil had occurred instead, even through the presence of thymine does lead to a greater expenditure of energy during the production of DNA.

These considerations, at best, account for the presence of thymine rather than uracil in DNA. They do not account for the presence of uracil in RNA. This is provisionally accounted for the following manner. A strand of DNA has a long existence, usually for about the same time as the life of the cell in which it occurs. RNA, on the other hand, is short-lived: a strand of RNA merely has to retain its form for the time it takes it to move from its source DNA to a ribosome and for the time it requires for translation to occur at the ribosome. Further, from each strand of DNA numerous strands of RNA are transcribed for translation at the ribosome. Therefore, the lesser stability of the code, as represented in the RNA, which results from the occurrence of uracil instead of thymine, almost never results in the production of a polypeptide chain with an altered amino acid residue sequence. Therefore, the extra energy expediter that would be necessary for the formation of thymine-containing RNA is not warranted. Given all of these considerations, the provisional explanation of the source of the difference between DNA and RNA is finally complete. The presence of thymine in DNA ensures greater stability of the code incorporated in it, which more than compensates for the additional energetic cost of the production of thymine from uracil. Uracil is present in RNA since the added stability that thymine would provide does not warrant the additional energy expenditure for the short-lived RNA.

There are five features of this explanation that need to be noted. *First*, the explanation appeals to *results, effects*, or *consequences* of the difference between RNA and DNA. The *effect* of the presence of thymine in DNA is the greater stability (as compared to RNA) of the code incorporated in that DNA.

[9] A mutation is "silent" when it does not alter the particular a nino acid residue which that codon (consisting of three nucleotide bases) codes for. This is possible because the genetic code is degenerate, that is, different codons often code for the same amino acid residue.

On the surface such an explanation appears not to be *causal*: the offered explanation does not appear to be only in terms of antecedent factors which is required by virtually any explication of causality.

Second, not all effects of the difference between DNA and RNA – for example, the difference in molecular weight – are relevant for the explanation. The kind of effect that enters into the explanation is called a *function* and explanation of this kind are called *functional explanations*. Functions, then, are certain effects of some feature of the organism (or part of the organism), and for functional explanations to be offered therefore, it becomes incumbent to provide a method by which functions can be distinguished from other kinds of effects.

Third, it is important to note that the explanation offered depends on a wide variety of factors including, for example, the nature of the mechanism that repairs DNA by recognizing uracil and replacing it with cytosine. In general, factors such as these, which provide the context in which functional explanations can be offered, are critical to the adequacy of such explanations. All three of these points will be addressed by the explication of functional explanation adopted later in this section.

Fourth, what has been offered so fair is only one example of a functional explanation in a molecular biology. However, other examples abound. The most important of these refer to the various schemes that are offered to account for the properties of the genetic code. For instance, the nature of the degeneracy of the genetic code is such that even when mutations are not silent, most of them will result in the replacement of a hydrophilic or hydrophobic amino acid residue by a residue of a similar type in the ensuing polypeptide chain. Moreover, since the genetic code is non-overlapping, a mutation, even when it is not silent, affects only one residue in the corresponding polypeptide chain. Both of these observations are routinely explained by noting that the nature of the genetic code is such that it functions to maintain the fidelity of the relation between a particular strand of DNA and to polypeptide chain as much as possible[10].

Fifth, in the example being discussed in detail, and in the other examples considered in the last paragraph, the question that was being posed was always one about the existence of some feature, whether it be of DNA and RNA or the genetic code. This suggests that functional explanations are offered in molecular biology only in response to such questions which can be called

[10] Explanations of this type lie at the core of the "selectionist" school of thought regarding the origin of the genetic code. More details of these explanations and regarding this school can be found in Lewin (1974, p. 34-36).

"questions of origin". In section 3, a general argument is given that attempts to show that this is so. For the rest of this section it will simply be assumed to be true. This does not entail, however, that attributions of function can only be made in the context of answering such questions. The attribution of functions and the use of such attributions in *functional explanations* are separate issues, though the former is necessary for the latter. Functional attributions can occur without attempting explanations: the issue of answering questions of origin, as will be argued in Section 3, arises only when such attributions are made as part of the process of explanation.

Various explications of functional explanations have been offered in order to ensure their causal adequacy. The one adopted here (with notational modifications) is due to Wimsatt (1972) which has the dual advantage of treating functional attribution as having explanatory power and giving a very detailed treatment of the contextual requirements for the adequacy of a functional explanation[11]. Intuitively, the idea behind this explication is quite simple. What requires explanation is the existence of some feature of a biological entity that is being investigated in molecular biology. A causal chemical theory, which need not be any more than a description of chemical mechanisms (the theory *T*, in the characterization below), identifies the effects of the various properties of this feature in the relevant chemical or biological circumstances[12]. A second causal theory (*T'* in the characterization below), which is the theory of natural selection in the case of molecular biology, determines which of these effects count as functions. As is conventionally assumed, only those effects that enhance the fitness of the entity involved are considered as functions. Since fitness is correlated with the probability of survival, the identification of some effect of a feature of the entity in question as a function explains, at least partially, the existence of that feature. Thus functional attribution plays a critical role in such explanations.

More formally, Wimsatt's explication attempts to provide a causal warrant for a functional explanation by invoking true "function-statements" of the form: "According to theory *T*, a function of feature *x*, in having property *Y*, in system

[11] The first of these advantages is lost in the analysis of functions which sees functional behavior as "goal-directed" behavior used by Rosenberg (1985) following Nagel (1961). Functional attribution then becomes nothing more than a redescription of goal-directed behavior which is shown to be causally produced. Functions thus loose the explanatory force that is usually attributed to them in biology. The second of these advantages makes Wimsatt's explication preferable to a very one due to Cummings (1975) which relies on the "wider context" to provide information about functional attribution but leaves the notion of the "wider context" embarrassingly vague.

[12] The term, "theory" is being used somewhat loosely here. This point will be taken up in the following note.

S, in environment *E* relative to purpose *P* is to bring about consequence *C*" (1972, p. 32). The theory *T* is required to be causal. Thus, it ensures that the consequence *C*, which can, for all practical purposes, be identified with the function under consideration, like all other effects of the feature *x*, in these circumstances, is causally "brought about". A second causal theory, *T'*, usually some sort of a selection theory, whose role is explicitly acknowledged in this explication, must fulfill two aims. *First*, it must already have shown which effects or consequences of the feature *x*, having property *Y*, in the environment *E*, are to be considered as functions with respect to purpose *P*. Thus it permits the choice of certain effects or consequences as functions which was earlier shown to be necessary for adequate functional explanation. *Second*, it must specify the purpose *P* satisfied by the function in question and the way in which it is satisfied, namely, the consequence *C*. When *T'* is a selection theory, as is the case in almost all biological contexts, the relevant purpose *P* is always to increase fitness. Note that the theory *T* permits the construction of sentences formally similar to function-statements for any effect of the feature *x*, having property *Y*, in system *S*, in environment *E*. Only when it works in conjunction with the theory *T'* do purposes and functions get identified and actual function-statements can be constructed. The function-statement answers the question of origin being raised simply because *T'* specifies the purpose *P* to be one of increasing fitness which is correlated with a higher probability of survival and, therefore, existence.

In the case of functional explanations in molecular biology, the theory *T* is the chemical theory that specifies the mechanisms which ensure that the feature *x*, in having the property *Y*, in system *S*, in environment *Y*, causes the consequence *C*. *T'* is simply the theory of natural selection: it requires that some feature *x*, in having the property *Y* in these circumstances, is functional if the consequence *C* enhances the fitness of the organism in question. In the case of the difference between DNA and RNA, the feature *x* is the occurrence of thymine in DNA. The purpose *P* is, of course, to increase fitness. The property *Y* is the ability of thymine to resist excision by the enzyme that excises uracil from DNA. The system *S* is the strand of DNA. The environment *E* is the cell environment including all the various enzymes required for the excision of uracil and the incorporation of cytosine in its place in the DNA. Finally, the consequence *C* is the possibility of repair of DNA after deamination of cytosine. For the functional explanation in question to work, two conditions must hold. *First*, the function-statement characterized by these assignments must have empirical support. This is ensured by the empirical truth of the chemical theory *T* that was invoked. *Second*, the theory *T'*, which, in this case, is the theory of natural selection, must also similarly be empirically true.

It is easy to see how this explication of functional explanation addresses the first three features of functional explanation that were noted above. *First*, this explanation is causal even though it explicitly invokes consequences or functions simply because the two theories that are involved are both causal. *Second*, it is explicit that the theory *T'* determines which effects of feature *x*, having the property *Y*, in the relevant circumstances constitute functions. *Third*, this explication invokes the environment *E* and the system *S* thereby emphasizing the various contextual factors that have to be considered in judging the adequacy of functional explanations.

The discussion in this section has demonstrated the existence of functional explanations in molecular biology and has outlined the requirements that must be satisfied in order to ensure their causal adequacy. Nothing has yet been said regarding the issue of reductionism. The question that is at stake here is whether the structure of functional explanations in molecular biology, as explicated above, can be captured by any explication of reduction from the category of explanatory reductionism[13]. There are two theories that play a critical role in this explication of functional explanation. The first of these, *T*, is the chemical theory which ensures that the particular feature in question, in the appropriate circumstances, causally produces the consequence which is identified as a function. Clearly, this should not present any problems for an explication of reduction from the category of explanatory reductionism. In fact, since this is a chemical theory, which explains at the chemical level, often through the description of appropriate mechanisms, a failure of a particular explication of reduction from the category of explanatory reductionism to capture such an explanation would only militate against that explication.

It is the *second* theory invoked in the explication of functional explanation given above, namely *T'*, the theory of natural selection, that presents serious difficulties. The theory of natural selection is obviously neither a physical nor a chemical theory. There is considerable controversy over exactly what the

[13] It can, of course, also be asked whether the structure of such explanations can be captured by some explication of reduction from the category of theory reductionism. This seems impossible for basically the same problem cited by Hull (1972) and Kitcher (1984), that is, the absence of appropriate theories. First, what is being explained is the existence of some feature. I take it as uncontroversial that a statement asserting this existence is certainly not general enough, nor has the kind of organizing power, to be designated a "theory". Further, though Wimsatt's explication refers to a "theory" T, the chemical theory involved, the intent of his explication includes the possibility that this theory is merely a description of known mechanisms and thus not a "theory" in any significant sense. In any case, even if these claims prove controversial, they do not affect the main thrust of this paper which is to question the ability even of explications of reduction from the category of explanatory reductionism to capture the structure of functional explanations in molecular biology.

structure of the theory of natural selection is[14]. It is uncontroversial, however, that this theory, broadly construed, requires that differential fitnesses of entities, in specified environments, causally produce differential probabilities of survival. It is in this form that the theory enters the explication above. However, the theory, as stated, is not capable yet of receiving physical or chemical explanation. Thus, no model of reduction from the category of explanatory reductionism can capture the structure of any explanation that critically involves the theory of natural selection[15]. Thus functional explanations pose a new sort of problem for the program of construing the structure of explanations in molecular biology as reductionist even in terms of an explication of reduction from the category of explanatory reductionism.

3. THE SCOPE AND POWER OF FUNCTIONAL EXPLANATIONS IN MOLECULAR BIOLOGY

The last section has shown that there exists a class of explanations in molecular biology, namely, functional explanations that cannot be captured by any explication of reduction from the category of explanatory reductionism. To judge the importance of this situation to the program of construing explanations in molecular biology as reductionist, it becomes incumbent to attempt to determine how large this class is. It has already been indicated in the last section that this class consists of attempts to answer questions of origin. However, no argument was offered in defense of this claim and this is the first task that is taken up in this section. It is later argued that functional explanations might only provide incomplete answers to questions of origin.

In order to argue that functional explanations occur in molecular biology only in response to questions of origin, it is not enough simply to list a number of functional explanations and show that they all occur in this way. Even if all known functional explanations were adduced, the possibility that there might yet be some functional explanation that serves some other purpose is left open. Thus, some more "transcendental" argument is necessary and the one to be offered here relies on a distinction between *questions of mechanism* and *questions of origin*.

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[14] Rosenberg (1985) and Ruse (1973, 1988), for example, present two radically different points of view. Rosenberg endorses an axiomatization due to Williams (1970) that finds no role for ordinary population genetics. Ruse holds that population genetics lies at the core of the theory of natural selection (and evolutionary theory in general). This controversy is yet to be resolved.

[15] The force of this conclusion will be mitigated somewhat, though only in the context of molecular biology, by the considerations adduced in Section 4.

Questions of mechanism arise when the behavior of some feature of an organism is probed with the purpose of discovering how it occurs or is accomplished. Thus the question how ions are transported across the cell membrane of bacteria or how the eye of some animal processes light signals is a question of mechanism. To begin to answer these questions, a mechanism for the transport of small charged particles across a bilipid layer and a mechanism showing how photons cause electric signals in optic nerves have to be elaborated.

On the other hand, one can ask why fetal hemoglobin differs from hemoglobin A in humans or why a codon has three bases. These are *questions of origin*: they probe the source of a particular feature of an organism. Elaborating mechanisms that describe results of these features – how fetal hemoglobin and hemoglobin A have different affinities for oxygen and carbon dioxide in different ionic environments or how triplet assignments lead to the possibility of degeneracy in the genetic code – obviously do not, by themselves, answer the pertinent question: why these features are there in the first place. Even elaborating the process (or mechanism) by which such features are produced, such as listing different genes that code for hemoglobin A and fetal hemoglobin, might not, depending on the context, be an adequate answer though it does appear, in some sense, to answer the question why there is a difference between these two molecules. For what might be being asked are the much harder questions, namely, why there are two hemoglobins and not just one and, assuming that this question receives a satisfactory answer, a second one, why the two hemoglobins differ exactly in the way they do. This point becomes even more explicit in the case of the triplet codon: clearly what is being asked for are not some mechanisms that produce DNA, RNA, ribosomes, or the enzymes involved in replication, transcription and translation. What is at stake is why each codon has three (and not, for instance, one, two, or four) bases. To answer that question is to speculate about the origin of the genetic code which is a much harder question.

Functional explanations occur in molecular biology only when attempts are made to answer questions of origin[16]. Consider any question of mechanism: what is being probed is how some particular behavior of an organism (or its

[16]There is also a third type of question that might arise within the context of molecular biology and which is of some relevance. These are *questions of persistence*: they probe why an organism (or part of an organism) *continues* to have some feature that it does. A question of persistence is actually a part of origin. This point will be discussed in the text later. That questions of origin can be separated into questions of initiation and questions of persistence does not, in any way, affect the analysis of them that is attempted here.

part) occurs or is accomplished. To offer a functional argument towards that end would be either to elaborate some function of that behavior or to show that the behavior under question is the function of some other process. The first alternative obviously does not answer the question that is being asked. A function is a particular result or effect of a feature of an organism (or its part). Even a list of all such effects of the feature, that is, the behavior, which would automatically include all possible functions, would not be itself explain how such behavior is brought about which was the question being asked. The second alternative is more interesting, though equally inappropriate. Suppose the question asked concerned the transport of ions across cell membranes of bacteria and, for the sake of simplicity and exactness, the question was restricted to the case of *E. coli*. If it were asked how such transport occurred, the following sort of functional argument might be offered. There are several proteins, notably the colicins, whose function, when attached to cell membranes of *E. coli*, is to form channels for ion transport (Cleveland et al. 1983). These proteins do attach to cell membranes of *E. coli* and, because of their function, the transport of ions takes place. There are two problems with such a response: in one sense it goes to far, that is, the invocation of function is gratuitous and unnecessary, and in another sense it does not go far enough because, while it begins to give the required answer, much more can be said even at the present stage of biological knowledge. The attempted answer goes too far because it would be enough, as far as explaining how the behavior of ion transport is brought about is concerned, merely to state that the effect of the attachment of the colicins to the cell membranes of *E. coli* is to produce channels for ion transport without having to decide whether this effect is one that can be called a function. In fact, in this example, when colicins are present, the channels produced almost always lead to the death of *E. coli* because all the ions necessary for the functioning of the cell leave its interior through these channels – it would be odd to call such an effect a function, to say the least. The sense in which the answer does not go far enough is that what might be being asked for is more detail, that is, how the colicins attach to the cell membrane and, exactly how, by their conformation or other interactions, they cause channels to be formed for ion transport.

The problem with the first alternative in the discussion above shows that the function of a particular behavior of an organism (or its part) does not address the question how it is brought about. The second alternative does address this question but the first problem with the answer to the question raised by it, demonstrates that functional considerations are unnecessary when attempts are made to answer questions of mechanism. Taken together they show that functional explanations cannot be adequate when offered as answers to

questions of mechanism. Thus functional explanations can, at most, only be offered in response to questions of origin. Even here, however, as will be discussed below, they might provide only partial answers and, sometimes, no answer at all.

It is important to note that trying to decide whether some particular question that is asked is a question of mechanism or a question of origin depends critically on the context in which the question is asked and can be non-trivial. It might, for example, be tempting to think of questions of mechanism as "*how*-questions": *How* does an organism (or part of an organism), *O*, perform behavior, *B*?"; and questions of origin as "*why*-questions": "*Why* does an organism (or a part of an organism), *O*, have feature, *F*?". The distinction between "feature" and "behavior" in these questions is not important: features can include behaviors as will be evident in the example discussed below. However, such an analysis of questions of mechanism and questions of origin is simplistic because it ignores the context in which the question is asked. Though *how*-questions are usually questions of mechanism, *why*-questions can routinely be either depending on the context. The last point is illustrated by the following example. Hemoglobin A is known to exhibit the Bohr effect. When the concentration of oxygen is high and carbon dioxide low, giving rise to a high pH (or low hydrogen ion concentration) in an aqueous environment, hemoglobin A has a lower affinity for carbon dioxide and a higher affinity for oxygen than in the reversed situation. Since oxygen concentration is high and carbon dioxide concentration low in the lungs, and the opposite is true in the capillaries, this property makes hemoglobin A admirably suited to transfer oxygen from the lungs to the tissues and carbon dioxide back from the tissues to the lungs. Now consider the question: "Why does hemoglobin A exhibit the Bohr effect?" It can either be a question of mechanism or a question of origin depending on the context. If it is the former, then the answer to the question involves, for example, elaborating the quaternary structure of hemoglobin A, that is, the joint conformation of the four amino-acid chains that compose hemoglobin A, and how this leads to allostery, that is, the assumption of different conformations in different environments, which in turn physically accounts for the changed oxygen affinities. If, on the other hand, the question being asked is a question of origin, then the answer to it involves the elaboration of the importance of this property of hemoglobin A in the functioning of the circulatory system and, therefore, why a molecule of this sort is suited to it. The context in which the question was asked determines which of these answers was being asked for, and unless that context is specified, there is no way of determining whether the question asked was only of mechanism or one of origin.

These considerations do not, of course, deny that the elaboration of mechanisms can be quite crucial in answering questions of origin. An exact and detailed knowledge of the interactions of some feature of an organism (or a part of an organism) can be necessary even to determine if that feature has a function. Sometimes the knowledge that is required is so detailed that it must be at a molecular level. In the example of the uracil-thymine difference between RNA and DNA, only when details of DNA repair were discovered at the molecular level, that functional considerations could begin. The point, however, is that when functional explanations are offered to answer questions of origin, just a complete knowledge of the various mechanisms involved is not enough for adequate explanation.

The discussion so far in this section has limited the role of functional explanation to answering questions of origin. However, even in this role, there are three factors that make the success of functional explanations often open to question. *First*, since the theory of natural selection plays such a crucial role in providing a warrant for functional explanations in molecular biology, those features of the organism (or its part) that exhibit functional behavior must be adaptive. Moreover, since functional explanations are offered in molecular biology specifically to answer the questions of the origin of those features, it has actually to be shown that those features rose by random variation, and were immediately and consistently adaptive for that function, in order for such explanation to be adequate. Thus, these features have to be adaptive in a stronger sense than is normally used. This point is made clearer by using a distinction initially made by Gould and Vrba (1982), that between *adaptations* and *exaptations*. A feature that is functional, at the present time, as indicated by the theory of natural selection, could have originated by random variation and subsequent selection for that function, or it could have originated in some other fashion though it might now be persisting because of selection for the current function[17]. The former are *adaptations*. The latter are *exaptations* and might have arisen in a variety of ways: they might have initially been created by random variation and selected for some other function that the present one, or they could have arisen out of some other kind of process – perhaps a purely physical process – and are only being subjected to selection constraints now. Functional explanations are adequate as answers to questions of origin in this stricter sense of the term. If a feature is functional in some specified way but arose through some other process, citing the current

[17] In the latter circumstance, the question that might be asked and be answered by functional explanation is a question of persistence (see note 16).

function clearly does not provide a complete answer to the question of its origin.

The last point leads to a *second* factor regarding the success of functional explanations in answering questions of origin: a particular functional explanation might only provide a partial answer to the question of origin that was posed. Gould and Vrba give the example of repeated segments of DNA which might have arisen simply because they did not code for any polypeptide chain and were thus virtually invisible at the phenotypic level. Therefore, there were no selection constraints, except the obvious weak energetic ones, to prevent their accumulation. These strands might now have the function of providing multiple copies of genes that code for particularly important proteins. To answer the question of their origin, that is, why they now exist, the functional explanation with respect to their current function which explains their persistence *and* the account of their initial creation and accumulation must both be given. Thus, when only exaptations are involved, functional explanation with respect to their current function only provides an incomplete answer to the question of their origin.

Third, it could be the case that a question of origin of some feature might have no functional explanation as an answer. For example, the so-called mechanistic models for the origin of the genetic code, which claim that there is a specific physico-chemical relationship between a codon and the amino acid residue it codes for (perhaps mediated by a complicated pathway), account for the origin of the degeneracy of the genetic code without invoking any functions at all (Lewin 1974, p. 34-36). According to these models, since there is a physico-chemical relationship that assigns an amino acid residue to a codon, the fact that there are six different codons for leucine, serine, or arginine, for example, is explained by the physico-chemical characteristics of those codons, these residues, and the expression pathways, and have nothing to do with the effects or consequences of this degeneracy[18].

The last factors considered reinforce a point noted in Section 2, namely, that functional attribution, by itself, need not have anything to do with answering a question of origin. If the theory *T'* in the explication adopted in Section 2, which permits identification of "functions" is a *selection* theory, as is usually the case in *biological* contexts, then functional attribution can be connected at least to the persistence of some feature, if not the origin. If this theory is not a selection theory, this connection cannot necessarily be made. Further, a distinction has to be maintained between functional attribution and the use

[18] Similarly even questions of persistence might not have adequate answers in terms of functional explanations.

of such attribution as part of functional *explanation*. If the argument given earlier in this section is valid, then functional *explanation* arises in molecular biology only in the context of attempts to answer questions of origin. In such a circumstance, since what is being asked is a question of origin, the purpose that a functional explanation serves is to answer such a question. This does not, in any way, preclude functional attribution in other contexts.

4. MOLECULAR EVOLUTION AND THE POSSIBLE RECOVERY OF EXPLANATORY REDUCTIONISM

The argument given in Section 2, against the possibility of capturing the structure of functional explanation in molecular biology by any explication of reduction from the category of explanatory reductionism, relied on the impossibility of a physical or chemical explanation of the theory of natural selection at the present time. There is a possibility that, at the *molecular level* at which molecular biology generally operates, this difficulty might eventually be overcome. However, it should be emphasized that this possibility is yet far from being actualized and is being offered here only as a very optimistic, and perhaps not equally realistic, promissory note. Since this possibility has already been discussed, with appropriate technical detail, in the philosophical literature (Sarkar 1988), only a very brief and informal discussion will be offered here for the sake of completeness. The relevance of this possibility to the program of construing the structure of explanations in molecular biology will then be discussed.

During the course of the development of a theory of the origin of life, Eigen and co-workers (Eigen 1971, 1983) have elaborated a theory of molecular evolution that can easily be separated from the particular initial conditions making it attractive as a theory of that origin (Sarkar 1988). Basically, this theory considers chemical systems where different nucleotide chains replicate, either by autocatalysis, or by the production of complementary intermediates as in the case of DNA replication in contemporary organisms. If the same number of different types of nucleotide chains are initially present, their relative frequency in subsequent generations need not be the same if available resources for replication, such as the number of nucleotide bases or available energy, is limited. In such circumstances, the relative frequency of a particular type of nucleotide chain will be proportional to the ratio of its formation rate to the average formation rate for all types, all other factors being constant[19].

[19] Of course, all other factors need not be constant. The relative frequency will vary inversely with the ratio of its spontaneous decomposition rate to the average such rate, for instance. For details, see Sarkar (1988).

Thus the "fitnesses" of these types can be defined using purely physical or chemical concepts. What results is a physical theory of natural selection of molecular species[20].

Now imagine that strands (or species) of two different types of DNA, "DNA_t", containing thymine, and "DNA_u" containing uracil, were undergoing replication in a chemical environment containing the enzymes responsible for replacing uracil by cytosine. After several generations, the proportion of DNA_t to DNA_u would have greatly increased because the total rate of production of DNA_u would be much lower than that of DNA_t simply because strands of DNA containing uracil would constantly be transmuted to some other species by the repair mechanism. Therefore, the fitness of DNA_t species is greater than that of DNA_u species in this environment. Note, now, that the theory of natural selection that is involved in the explication of functional explanation becomes, in these circumstances, a purely physical theory. Thus the difficulty, mentioned in Section 2, about the possibility of capturing the structure of functional explanations by some explication of reduction from the category of explanatory reductionism is removed. Further, since the chemical explanations involved in this account are so simple, virtually *any* plausible explication of reduction from that category would have to capture these explanations.

However attractive the sort of schema just given might seem, especially to committed reductionists, there are three very important reasons to be cautious about the success of such schema. *First*, the theory of molecular evolution that is being invoked here is still in its infancy and wanting in both theoretical development and, especially, experimental confirmation. Any use of it, especially to draw broad philosophical conclusions, must be extremely self-consciously tentative. *Second*, the particular example just discussed involves at least one very dubious assumption. This is that the two types of DNA mentioned were replicating in an environment that already contained the enzymes for the replacement of uracil by cytosine. It is hard – though not impossible – to imagine a situation in which such a system could have evolved at so early a stage of evolution of both types of DNA were present. *Third*, the physical explication of natural selection that has been utilized in this section is limited to the molecular level. There is no straightforward way to extend this to higher level of organization, such as the cellular or tissue levels, let alone the organismic and even higher levels. There is no reason to suppose that the selection constraints operating to ensure the adequacy of functional explanations in

[20] That what occurs is evolution by natural selection is shown by demonstrating that these systems satisfy the criteria for such evolution laid down by Lewontin (1970). This is done in Sarkar (1988).

molecular biology always involve only the molecular level. Thus, even if this theory of molecular evolution is fully successfully developed and confirmed, there might yet be cases of functional explanation in molecular biology that cannot be underwritten using only it and not invoking natural selection at some other level.

In any case, the purpose of this somewhat speculative section has been to show that *some* functional explanations in molecular biology *might eventually* be captured by explications of reduction within the category of explanatory reductionism. Perhaps the real moral to be drawn from this section is a simple and important one: the answer to some philosophical questions must necessarily await an answer to scientific ones.

5. CONCLUSION

The main purpose of this paper has been to show that there exists a class of explanations in molecular biology, namely, functional explanations, whose structure cannot be captured even by explications of reduction from the category of explanatory reductionism, let alone theory reductionism. This has been argued for in Section 2. There it has been observed that the theory of natural selection plays a critical role in assuring the causal adequacy of functional explanations. Since this theory of natural selection is itself incapable, at present, of physical and chemical explanations, its use precludes the possibility of capturing the structure of functional explanations in molecular biology in the manner just mentioned. In Section 4, however, it has been argued that some such functional explanations might ultimately be captured by these explications of reduction though that will have to await the further development, and experimental tests, of theories of molecular evolution. Thus that section argues, in part, against the force that should be attributed the main conclusion of this paper.

However, a much more important limitation on the force of this conclusion comes from the considerations in Section 3 which restrict functional explanations in molecular biology to answering questions of origin. Therefore, in the final analysis, the extent to which this paper brings into question the program of construing the structure of explanations in molecular biology as reductionist, under some explication of reduction from the category of explanatory reductionism, depends on the importance of questions of origin in molecular biology. This is an issue that is not precise enough for any definitive decision. On the one hand most of molecular biology concentrates on questions of mechanism, in answering which it had some spectacular successes. On the other hand, questions of origin are of profound interest and have always been so in biology. It is likely, moreover, as knowledge of molecular mechanisms in-

creases and it becomes possible to give more definitive answers to such questions, they will continue to be more and more fruitfully asked. Thus, it seems reasonable to conclude that any point of view regarding molecular biology that ignores these questions, and their answers, is seriously mistaken. Among these would be a point of view that is so strictly reductionist, in the senses invoked under either category of theory or explanatory reductionism, that would simply abandon these questions in order to preserve a reductionist metaphysics.

It is possible, of course, that ultimately the theory of natural selection, at all levels, will be underwritten by physical theory. In such a circumstance no functional explanation will pose a problem to the program of construing explanations in molecular biology as reductionist under some explication of reduction from the category of explanatory reductionism. However, such a situation is not imminent in the near future. In the meantime, the thrust of this paper must be taken to be another attack, though a limited one, to the notion that explanations in molecular biology are always "reductionist" even under the construal of that term by explications of reduction from the category of explanatory reductionism.

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