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The Theory of Biology and the Education of Biologists: a case study

ABSTRACT

A set of questions on evolutionary theory and the philosophy of biology was given to students of zoology at three levels: third-year undergraduates (23); fourth year, honours (13); graduates (25). Answering was voluntary. The responses were assessed independently by a zoologist, an educator and a philosopher. None of the students failed conventional courses, but each author 'failed' nearly half the students; sixteen were 'failed' by all three authors.

There was little evidence of a general, critical understanding of the concept of natural selection. About two-thirds of students accepted natural selection as an axiom or dogma. About half understood 'tautologous'. Most students regarded physics and biology as fundamentally similar, and more than half held all biology to be ultimately reducible to physical science. Very few understood the significance of refutable propositions in science.

We suggest that these findings reflect a general trend, related to the specialisation of biological teaching; and that teaching deficient in theory both influences research strategies and also impairs the ability to cope with questions of social importance.

In 1979, during informal discussions, several graduate students of zoology in the Australian National University suggested that their training was excessively narrow: they were beoming specialists who knew little even of general biology, let alone wider matters. Then, as now, there was much debate on the use of biological concepts to interpret human social action. The most prominent concept used in this way was that of natural selection. At the same time the theories of evolution themselves had once again become sources of controversy, both among biologists and philosophers on the one hand, and laymen, on the other (see, for example, Grene, 1981; Waddington, 1969; Wasserman, 1978).

An empirical question was raised by the students' complaint. To what extent did the zoological curriculum equip them to answer questions on biological theory and philosophy? Such a question has implications wider than those concerning the teaching of biology. Science education in general has been under heavy fire for giving mere lip service to 'guided discovery' and 'concept learning' (for example, Novak, 1977; Schwab & Brandwein, 1966; Suchman, 1968). Hence 'meaningful learning' and 'ability to undertake scientific enquiry and to apply the results' have more recently become commonplace objectives of advanced science courses. But there is still doubt about the extent to which science teaching in the universities takes concept formation and conceptual reasoning into account (Hegarty, 1978). At a time of struggle to maintain even traditional specialised teaching, it would not be surprising if many university teachers preferred to brush such questions under the carpet.

In 1980, a questionary (designed by the zoological author) was issued to students of zoology at three levels: third year, honours (fourth year) and graduate. It was made clear that answering was voluntary: the students were not being examined, but were helping in research. Nearly all students finished the questionary within an hour. All seemed to take an interest in the project.

The members of the first group were taking a semester course in theoretical zoology, designed for students intending to take honours. For admission to the second group (honours), a student was required to show promise of achieving at least an upper second class degree. Most of those in the third group were working for Ph.D., some for M.Sc. (which, too, is a research degree). Eight graduates were from outside Australasia. Most of the graduate students had achieved a first class honours degree or its equivalent.

In addition, twelve members of the teaching staff of the Zoology Department were asked to fill in the questionary; seven responded.

The questions were on biological theory or the philosophy of science, especially in relation to ideas about evolution. The answers were analysed in objective, numerical terms; and they were also assessed independently, as if presented for examination, by the three authors: a zoologist who specialises in animal behaviour, an educator who works on adult learning, and a philosopher with special interest in the contribution of biology to the social sciences. Each assessment was made in ignorance of the status (or name) of the student.

The students were probably a representative sample of those learning biological science in 'Western' universities. From the foundation of the department in 1963, to 1981, an honours degree was completed by 171 students, of whom 41% were women. Thirty-one per cent were put in the first, 17% in the lower second class. Fifty-three per cent of honours students took higher degrees (nearly all Ph.D.), not all in the department; 32% were employed, immediately after graduation, in universities, the public service or paramedical work. On 16% we have no information. Of 50 Ph.D.s and 11 M.Sc.s who graduated from the department, only two (both married women) did not at once take up paid work, nearly always in tertiary teaching, research or the public service.

If the department studied was atypical, it was in an especially strong emphasis on parasitology and on comparative physiology and biochemistry.

Our Presumptions

Table I gives the questions. We now state the presumptions that underlay them.

There are two 'theories of evolution'. First, all existing organisms have arisen, by a continuous process, from very different organisms in the past. The evidence for this is so strong that opposition is possible only by dogmatically rejecting the evidence and by presuming the existence of some transcendental agency. Second is the theory of natural selection. This, too, is a central concept of biology, but its definition is a matter of debate, and its scope, of investigation.

TABLE I. The questions

1a	'Statements on how characteristics have evolved, by natural selection or otherwise, cannot be tested.' Comment on this statement in about three sentences.
1b	'The theory of natural selection can be stretched to explain anything.' Comment in, say, two sentences.
1c	'The theory of natural selection is tautologous and explains nothing.' Comment in about three sentences.
1d	'No true biologist accepts the Lamarckian theory of organic evolution.' Comment, in about two sentences each, on (i) the biological content of this assertion, (ii) its logical status.
2	'The physical and biological sciences are fundamentally different: in the former the trend is towards theories of progressively higher generality and predictive power; in biology there is an accumulation of vast masses of facts about diversity.' Comment in not more than three sentences.
3	'All biological phenomena are in the long run explicable in terms of the physical sciences.' State (a) whether you agree and (b) the name given to this doctrine; (c) comment in one or two further sentences.
4	(a) 'The test of a scientific theory is whether it leads to correct prediction.' (b) 'A theory is scientific only if it can, in principle, be refuted.' Comment in not more than four sentences on these statements.

The first assertion in the questionary, that statements on how characteristics have evolved cannot be tested, is generally true: such statements are usually retrospective, and refer to events that cannot be repeated. But there are important qualifications: genetical changes in populations can sometimes be related precisely to phenotypic and environmental changes, and a few can be shown to be adaptive. Such changes may be regarded as examples of micro-evolution by natural selection.

The statement in 1b, that the theory of natural selection can be stretched to explain anything, is, on the face of it, absurd; but it can be answered seriously if 'anything' is taken to mean 'any feature of any organism'. The allusion is to statements such as those on the adaptive radiation of groups. The original mammals presumably lived on the ground and had teeth rather like those of modern shrews (Soricidae); but from them have arisen bats, whose structure was selected 'so that' they could fly, whales, whose structure was selected 'so that' they could swim... If we say *everything* has been 'selected', or is 'adapted', we make no useful distinction; and we throw no light on how evolution has occurred.

Question 1c, on natural selection and tautology, alludes to the fact that there is no completely satisfactory, formal, rigorous statement of the theory of natural selection (Maynard Smith, 1980). For example, 'natural selection is an inevitable consequence of genetical variation in fitness' (Waddington, 1939, p. 299). Such a statement, logically analysed, is tautologous: it is a definition of the term natural selection, and says nothing about what happens in actual populations. But the theory may be held to make an empirical statement also: that, as a result of the existence of genetical variation in fitness, populations change progressively. This is a (hypothetical) explanation of the fact of evolution.

The statement in 1d, that no true biologist accepts the Lamarckian theory of organic evolution, raises a familiar biological question that can be expressed as follows: can adaptation during ontogeny, that is, individual development, (for example, to an altered environment) lead directly to a genome so changed that the offspring retain the new adaptive features of the parents without themselves undergoing the same ontogenetic process? Despite recent debates among immunologists, the answer remains no.

The logical content of the statement is more tricky: formally, it could be regarded as a stipulative definition of the term 'true biologist'; but usually an assertion of this sort represents a moral exhortation: 'No true gentleman strikes a woman'. We do not, however, consider it morally wrong to propose neolamarckian hypotheses, although we suspect some biologists do. Indeed, for certain prominent biologists, natural selection has represented, not merely a biological hypothesis, but a transcendental principle—'a surrogate for divine providence' (Flew, 1974, p. 231).

The proposition in question 2 alludes to the distinction between 'natural science' and 'natural history'. In the former, the aim is to achieve theories or laws of progressively higher generality. The obvious biological examples are from genetics and perhaps biochemistry; but the theories of evolution also qualify in principle. 'Natural history' is concerned with diversity.

The statement that in biology there is an accumulation of facts is correct: diversity is indeed studied, both as a subject in itself and as a prerequisite of evolutionary change. Hence follows the importance, in biology, of statistical analysis, and the fact that in biology it is more difficult than in physics to establish major laws of high generality. There is, in fact, a clear, though not sharp, difference between the biological and the physical sciences.

Extreme reductionism (question 3) is untenable, if only because, if *all* biological phenomena are reduced to physics and chemistry, then no organisms remain to be explained (see, for example, Grene, 1974; Medawar, 1974). Statements on (say) biochemistry often acquire significance only when they are related to the activities of whole organisms. It is, however, a truism that all biological phenomena have physico-chemical components.

Questions 4a and 4b, on prediction and refutation, can be interpreted in various ways. We illustrate them from 4b. First, 4b could be held to state that an irrefutable theory is a Bad Thing. On this we comment only that much depends on just how irrefutable theories are used: they sometimes suggest fruitful investigation. Second, 4b could be a statement on what scientists do. If so, it is incorrect: when a new finding seems to invalidate a theory, often the theory is not discarded; instead, subsidiary hypotheses are proposed. The standard examples concern the orbits of the planets. Another is the existence of bioaltruistic behaviour in the social interactions of many animal species. This seems to refute the theory of natural selection; but neodarwinian theory is nonetheless retained, and attempts are made to show that what is the case is also theoretically possible (reviewed by Barnett, 1981).

Lastly, 4b may be regarded as a statement that distinguishes categories of propositions. It is then an example of *classifying*. The importance of classification is, we think, often underrated, or at least disregarded. The distinction between statements that can be refuted and those that cannot is a useful one to make (Popper 1972).

Assessment

The three authors assessed the answers independently, each by his or her own criteria: as a result, there were clear differences of method. Each complete set of answers was graded α, β or γ. The criteria follow.

Zoologist. α: understanding of modern theories of evolution and of the philosophical questions mentioned; clear expression. β: some understanding and serious attempt to answer questions. γ: inability to see the point of the questions.

Educator. α: evidence of consideration of relative weights of the evidence: selection and defence of a tenable point of view. β: recognition of possibility of more than one position or interpretation of a question. γ: polar attitude, answers dogmatic.

Philosopher. α: logical and imaginative responses; acquaintance with relevant biological knowledge. β: logical responses, some relevant knowledge. γ: inability to make thoughts clear.

Analysis of Answers

Table II summarises the grades given by the three authors. We each put fewer than one in four students in the top grade. More important, we each awarded γ to at least 25 of the papers: that is, nearly half of the total of 61 students were considered, by at least one of us, to have 'failed'; yet none of the students failed by ordinary academic criteria. There was, of course, some disagreement: only five students were awarded α by all of us; we were unanimous in 'failing' sixteen.

TABLE II. Grades awarded by the authors to all students
(N=61)

	alpha	beta	gamma
Zoologist	9	27	25
Educator	15	19	27
Philosopher	13	20	28

Table III gives figures on the answers to individual questions. The answers to questions 1a to 1d give some notion of the responders' grasp of evolutionary theory. On question 1a, a surprising number *agreed* that statements on how characteristics have evolved are untestable. Of those that disagreed, about half mentioned observations or experiments on micro-evolutionary change (genetical changes in populations) as evidence on the causes of evolution.

Question 1b was intended to test for awareness of a familiar critical comment on the way in which the presumption of natural selection is used. As an honours student wrote:

> True. Situations can be imagined where almost any present-day character in a species could be of selective value. This means that if any character is not obviously selected for, it can be claimed that it is present because it was selected for in the past.

In contrast, there were those (about two-thirds), who accepted natural selection as an axiom. We probably underestimated their number, because some answers were ambiguous, obscure or non-committal, and respondents were given the benefit of the doubt. Here is an unambiguous reply from a graduate student.

> If you are inferring [*sic*] anything biological, I think it can be stretched that far! All biological entities and processes that at present exist must be the cumulative effects of selection in terms of adaptation and competitive survival.

The answers to question 1c showed just over half the students to understand tautologous; rather more gave some statement on the concept of natural selection, and why its logic has been debated. For example, a graduate student wrote:

> If one assumes that natural selection is 'survival of the fittest' and the fittest are survivors then natural selection results in survival of the survivors.

No student, however, in answers to questions 1b or 1c, made a clear statement on the other difficulties raised by the concept of natural selection.

Question 1d presented the responders with several problems. Ten students, including one graduate, did not understand 'Lamarckian'. More than half the students accepted the statement: most of these evidently took it simply as the assertion that Lamarckism is wrong. Three undergraduates and eight graduates mentioned the debate on 'Lamarckism' then in progress among immunologists. Twenty-five criticised the word 'true': some

TABLE III. Summary of answers to questions
(The numbers that head the columns are of the questions in Table I.)

		1a		1b	1c		1d	2			3	
								Physics and biology differ				
	N	Agrees	Mentions micro-evolution	Natural selection as axiom	Under-stands 'tauto-logous'	Explains natural selection	Accepts state-ment	Agrees	Disagrees	Other	Accepts reduction	Reduct-ionism named
3rd year	23	9	10	9	12	13	11	5	9	8	11	1
Honours	13	6	4	6	7	10	6	4	5	4	5	1
Graduate	25	7	7	12	14	16	15	6	14	5	18	5
Staff	7	2	5	1	7	4	4	0	6	1	5	1

objected that its use implied an inappropriate value judgment; the others took the view that scientific method requires readiness to examine any hypothesis. Some, especially graduates, treated the statement about a 'true biologist' as providing a formal criterion for identifying a biologist.

The answers to question 2 showed a large majority holding physics and biology to be fundamentally similar. (It would be interesting to know whether this is because of the prestige of the physical sciences, or because of the certainty that the 'harder' sciences seem to provide.) But the most interesting and sophisticated responses neither agreed nor disagreed with the statement. A graduate wrote:

> Biological science is *limited* by physical science: we perceive living systems in mechanical terms and often fail to see synergistic relations, animal-animal interactions and so on.

And an honours student:

> All these methods are ways in which man can order his mind in order to categorise his environment.

The responses to question 3 were notable for the few who answered 3b with 'reductionism' or 'reduction'. One student and five staff members suggested 'mechanism' (a related and useful concept); other suggestions included 'fatalism' and 'capitalism' (a joke?). More than half the students accepted that all biological phenomena could eventually be reduced to physical science.

Question 4 presented the most severe difficulties, and the answers are correspondingly difficult to analyse. Seventeen students agreed that the test of a scientific theory is its predictive power, perhaps because, as an honours student irritably remarked, it had been taught as a dogma at school. Another honours student stated, more mildly, that she had learnt it at high school and had not considered it much since.

Question 4b baffled most of the students: 51 were clearly unfamiliar with its background and implications. One third-year student and four graduates (and three staff members) mentioned Popper. None of the others responded unequivocally in a way that suggested acquaintance with Popper's classification of hypotheses. A few, however, made intelligent comments. For example, a graduate:

> The use of the null hypothesis is a powerful tool, but it limits the type of questions that can be asked because of the physical difficulties of refuting it.
>
> Theories have values as conceptual models to allow us to organize our thoughts, even if theory cannot be proven or disproven.

Our findings do not allow firm conclusions on differences between the three populations of students. The proportion of alphas rewarded gave no evidence that the graduates were superior to the others. On the evidence of Table III, the differences between the three groups, if any, were minor—an interesting observation in itself. The graduates, however, were more prepared to distinguish theoretical features of the physical from those of the biological sciences; and they included a higher proportion of apparently uncompromising reductionists.

Discussion

Our enquiry originated in a complaint by graduate students that their education was excessively narrow. The findings suggest that their complaint was justified. Most of our questions tested knowledge of concepts central in biological science; and few students proved to have a satisfactory grasp of them. Of 61 advanced biology students, two-thirds accepted natural selection uncritically, as an axiom or dogma. (Many of the responses on reduction reflected a similar unquestioning commitment to a presumption.) Such presumptions are likely to influence the choice of scientific problems thought to be worth studying. The apparent tendency toward a higher incidence of reductionists among graduates perhaps corresponds to an unconscious bias in the teaching they received. This is one item, among several that arise from our study, on which there appears to be little empirical investigation.

The responses to the questionary also show that an enquiry of this kind can give information useful to teachers when they are designing courses. A single incident suggests one way in which the students' education could have been improved. One of the undergraduates had been taking a course in Human Sciences; and she remarked spontaneously that this interdisciplinary course was the one that had helped her to answer our questions. Though not outstandingly able, she was the only undergraduate who mentioned Popper. Here is her response to question 4:

> (a) 'Correctness' in whose terms? Statement (b) refer to Popper's Principle of Falsifiability. It has proved a useful method of inquiry but has its dangers, as Kuhn has pointed out. 'Facts', e.g. re-predictive power, are still often value-laden.

The significance of this response is in showing acquaintance with issues of which her contemporaries were unaware. Unfortunately, no other undergraduates had taken Human Sciences; hence no systematic study of its effects was possible. (For information on the course, see Barnett & Brown, 1981.)

Our findings are probably not peculiar to the small population we studied, but have a general application. Brumby (1981, 1982), has investigated first-year students studying biology in England (University of Surrey) and Australia (Monash University), and has found confusion about the concepts of evolution among them. Her findings conform with those of Johnson (1948), in Birmingham University, also on first-year students. On this evidence, there has been little improvement over three decades.

Our findings may also be considered in a context wider than that of a biological education. Perry (1970) has described stages in the intellectual development of students: the first is that of 'polar reasoning', in which questions are answered in black or white; from here students move to discussing a diversity of opinions; finally, some become able to argue a case, to allow for alternative positions, and to take responsibility for a preferred conclusion. In the present study the educator assessed the answers mainly for such general reasoning ability, and only about one in four of our students were judged to have reached the last stage; but this was a higher proportion than those assessed as first class by the zoologist (who was more concerned with the understanding of particular biological or philosophical questions).

Hence more students gave evidence of reasoning ability than of theoretical biology. Presumably, therefore, many students had the capacity to benefit from more theoretical teaching than they received.

Many university teachers would still question whether it is important that the theoretical foundations of biology should be taught. After all, as we show above, students with honours or higher degrees from the department studied have nearly always been able to take up socially acceptable and rewarding work. We believe nonetheless that knowledge of theoretical principles is important, in at least two ways.

(i) The choice of research project is often influenced by an unacknowledged, even unconscious, 'philosophy' or set of presumptions. (They may be the presumptions of a supervisor.) Uncompromising reductionism can lead to disregard of questions that cannot be answered at the chemical or physiological levels, or by mathematical calculation. Much current evolutionary research is on models of natural selection only tenuously related to empirical findings. It would be instructive to know the theoretical background against which people select this type of research.

(ii) Recent and current controversies on human biology expose a similar lack. *Homo sapiens,* like other species, is a product of evolution. It is taken for granted that we have evolved by natural selection; and on this presumption are founded wide-ranging interpretations of human societies, practices and attitudes in all their diversity. Such interpretations raise questions that biologists are often ill-equipped to answer: when the interpretations are based on inadequate theory, they are not merely wrong but also conceal the important issues (Barnett, 1979, 1983; Etkin, 1981; Schubert, 1981).

Intense specialisation is often necessary, and is increasingly forced on students by the advance of knowledge; but it can also be a severe handicap (Ashby, 1972). Our findings provide a glimpse of some of its effects. We hope that others will give these effects wider and more rigorous empirical study.

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REFERENCES

ASHBY, E. (1972) Science and antiscience, in: HALMOS, P. (Ed.) *The Sociology of Science,* Sociological Review Monograph No. 18 (Staffordshire, University of Keele).

BARNETT, S.A. (1979) Cooperation, conflict, crowding and stress: an essay on method, *Interdisciplinary Science Reviews,* Vol. 4, pp. 106–131.

BARNETT, S.A. (1981) *Modern Ethology: the Science of Animal Behavior* (New York, Oxford University Press).

BARNETT, S.A. (1983) Humanity and natural selection, *Ethology and Sociobiology,* Vol. 4, pp. 27–43.

BARNETT, S.A. & BROWN, V.A. (1981) Pull and push in educational innovation: study of an interfaculty program, *Studies in Higher Education,* Vol. 6, pp. 13–22.

BRUMBY, M. (1981) The use of problem-solving in meaningful learning in biology, *Research in Science Education,* Vol. 11, pp. 103–110.

BRUMBY, M. (1982) Students' perception of the concept of life, *Science Education,* Vol. 66, pp. 613–622.

ETKIN, W. (1981) A biological critique of sociobiological theory, in: WHITE, E. (Ed.) *Sociobiology and Human Politics,* pp. 45–97 (Lexington, Mass., Heath).

FLEW, A. (1974) Evolutionary ethics, in: HUDSON, W.D. (Ed.) *New Studies in Ethics,* Vol. II, pp. 215–286 (London, Macmillan).

GRENE, M. (1974) *The Understanding of Nature* (Dordrecht, Reidel).

GRENE, M. (1981) Changing concepts of Darwinian evolution, *Monist,* Vol. 64, pp. 195–213.

HEGARTY, E.H. (1978) Levels of scientific enquiry in university science classes, *Research in Science Education,* Vol. 8, pp. 45–57.

JOHNSON, M.L. (1948) Biology and training in scientific method, *School Science Review,* Vol. 108, pp. 139–147.

MAYNARD SMITH, J. (1980) The concepts of sociobiology, in: STENT, G.S. *Morality as a Biological Phenomenon,* pp. 21–30 (Berkeley, University of California Press).

MEDAWAR, P.B. (1974) A geometric model of reduction and emergence, in: AYALA, F.J. & DOBZHANSKY, T. (Eds) *Studies in the Philosophy of Biology,* pp. 57–63 (London, Macmillan).

NOVAK, J.D. (1977) *A Theory of Education* (Ithaca, N.Y., Cornell University Press).

PERRY, W.G. (1970) *Forms of Intellectual and Ethical Development in the College Years* (New York, Holt, Rinehart & Winston).

POPPER, K.R. (1972) *Objective Knowledge: an evolutionary approach* (Oxford, Oxford University Press).

SCHUBERT, G. (1981) The sociobiology of political behavior in: WHITE, E. (Ed.) *Sociobiology and Human Politics*, pp. 193–238 (Lexington, Mass., Heath).
SCHWAB, J.J. & BRANDWEIN, P.F. (1966) *The Teaching of Science* (Cambridge, Mass., Harvard University Press).
SUCHMAN, J.R. (1968) *Developing Enquiry in Earth Science* (Chicago, Science Research Associates).
WADDINGTON, C.H. (1939) *An Introduction to Modern Genetics* (London, Allen & Unwin).
WADDINGTON, C.H. (1969) Paradigm for an evolutionary process, in: WADDINGTON, C. H. (Ed.) *Towards a Theoretical Biology. 2. Sketches*, pp. 106–124 (Edinburgh, Edinburgh University Press).
WASSERMAN, G.D. (1978) Testability of the role of natural selection within theories of population genetics and evolution, *British Journal of the Philosophy of Science*, Vol. 29, pp. 223–242.