

DARWIN'S OTHER MISTAKE

Michael R. Rose and Theodore Garland, Jr.

CORRECTING DARWIN'S OTHER MISTAKE

DEFINITIONS AND CONCEPTS

**MACROEVOLUTION, MICROEVOLUTION,
AND THE ROLE OF SELECTION EXPERIMENTS**

**OVERVIEW OF THIS VOLUME: EXCLUSIONS
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Experimental Evolution: Concepts, Methods, and Applications of Selection Experiments, edited by Theodore Garland, Jr., and Michael R. Rose. Copyright © by the Regents of the University of California. All rights of reproduction in any form reserved.

We are taught early in our education as evolutionists that Charles Darwin got the mechanism of heredity wrong. He supposed that there are an arbitrary number of ductile transmissible gemmules that migrate from the organs to the gonads, allowing the possibility of a kind of blending inheritance along with the inheritance of acquired characters. Of course, Gregor Mendel's discrete "hard" model for inheritance, which we now call genetics, turned out to be the correct mechanism for inheritance in eukaryotes. Furthermore, Darwin's mistake about inheritance probably cost the field of evolutionary biology some decades of delay. Genetics wasn't properly incorporated into evolutionary biology until the work of Fisher, Haldane, Wright, and Dobzhansky, in the period from 1910 to 1940 (Provine 1971; Mayr and Provine 1980). Regrettably, the person who may have seen that genetics supplied the mechanism of heredity that Darwinian evolution needed was Mendel, a humble monk who died unappreciated in 1884, some twenty years after he had worked out the basic principles of inheritance in plants. If Darwin had read Mendel with understanding in the 1860s, it is conceivable that much of modern evolutionary biology would have developed some fifty years earlier than it did, although such counterfactual speculation is of course essentially an idle exercise.

One of the common themes in the classroom presentation of Darwin's erroneous reasoning concerning heredity is the influence of his gradualist prejudices. It is well known that Darwin was in many respects a disciple of Charles Lyell, the leading gradualist geologist of nineteenth-century England. Lyell essentially founded modern scientific geology. Darwin was Secretary of the Geological Society early in his career, a scientific society dominated by Lyell's thinking, particularly his methodological strictures. The cardinal axiom in Lyell's geology was the idea that change in nature proceeds by gradual, observable, concrete mechanisms. In geology, such mechanisms are illustrated by erosion, subsidence, deposition, and the like. Darwin imported this style of thinking into biology. This led him to disparage the importance of discrete heritable variants, which he called "sports." That, in turn, prevented Darwin from giving appropriate attention to the hypothesis of discrete inheritance, leading evolutionary biology up a blind alley of blending inheritance. This was the famous mistake that is a key motif in the education of beginning evolutionary biologists.

Darwin's other mistake also came from his gradualist preconceptions. He repeatedly emphasized that natural selection acts only by slow accretion (Zimmer 2006). Darwin expected the action of selection within each generation to be almost imperceptible, even if thousands of generations of selection could evidently produce large differences between species: "natural selection will always act very slowly, often only at long intervals of time, and generally on only a very few of the inhabitants of the same region at the same time. I further believe, that this very slow, intermittent action of natural selection accords perfectly well with what geology tells us of the rate and manner at which the inhabitants of this world have changed" (Darwin, *Origin of Species*, first ed., chap. 4). Notably, the word *slowly* appears dozens of times in the *Origin*.

For modern scientists, at least, the problem with this assumption is that it implies that the action of natural selection will normally be very difficult to observe. Indeed, Darwin himself made no significant attempt to study natural selection in the wild. Instead, he studied the systematics of barnacles, bred pigeons, and crossed plants. He was certainly interested in both the long-term effects of evolution and the short-term effects of crosses, but he did not apparently seek out opportunities to study the process of natural selection itself. The closest he came to this was collecting an abundance of information on artificial selection from breeders, both agricultural and hobbyist, and discussions of their various results figure prominently in the *Origin*.

This dereliction did not persist, fortunately. The Illinois Corn Experiment began bidirectional selection on oil content in 1896 (Hill and Caballero 1992). W. F. R. Weldon (1901) published a pioneering study of selection in the wild on the morphology of estuarine crabs. Botanists, such as H. de Vries, began various selection experiments (Falconer 1992). In 1915, W. E. Castle published reasonably quantitative data on the response to “mass selection” on coat coloration in rats. In the 1930s, animal breeders such as Jay L. Lush took up the quantitative genetics theory developed initially by R. A. Fisher to implement well-designed breeding programs. Theodosius Dobzhansky started the “Genetics of Natural Populations” series of articles in the 1930s, studying selection on the chromosomal inversions of *Drosophila* in both wild and laboratory populations, often enlisting the aid of Sewall Wright. Ecological geneticists such as E. B. Ford and H. B. D. Kettlewell studied industrial melanism, one of our best examples of natural selection in the wild (Clarke 2003). Starting from this wide range of groundbreaking work, evolutionary biology has developed into a substantial body of empirically founded knowledge.

But there remains a tendency to adopt unthinkingly Charles Darwin’s bias that natural selection is typically slow and difficult to observe. Very old patterns of research have persisted: studies of phylogenetics, genetic variation within and among populations, and occasional dramatic instances of natural selection in the wild have featured prominently in evolutionary research (Endler 1986; Hoekstra et al. 2001; Kingsolver et al. 2001). As these research paradigms have persisted, and indeed dominated within evolutionary biology, experimental evolution has been slow to develop as a research strategy. In 1976, M.R.R. did not consider trying selection for slowed aging in *Drosophila* because of the expectation that it would take too long to yield observable results. Reading about the results of an inadvertent and misinterpreted selection experiment by a neo-Lamarckian (Wattiaux 1968) in 1977 was the trigger that enabled M.R.R. to overcome his typical Darwinian inhibitions, leading to a deliberate test of Hamilton’s (1966) analysis of the evolution of aging using laboratory evolution (Rose et al. 2004; Rose 2005). Now, of course, such laboratory evolution experiments on life-history characters are common in evolutionary biology. It was the pioneering work of Carol B. Lynch (1979; review in Lynch 1994) that convinced T.G. that selection experiments were actually practical for addressing classic questions in physiological ecology. Now, selection experiments of various types are common in evolutionary physiology (Bennett 2003; Garland 2003; Swallow and Garland

2005; Swallow et al. this volume). Yet as recently as 2005, T.G. observed colleagues discouraging graduate students from undertaking selection experiments in this area. Old biases die lingering deaths.

It is our conviction that the Darwinian inhibition about experimental research on evolution should now be resolutely discarded. This volume is effectively a brief in support of this view and naturally enough part of our campaign to foster selection experiments and experimental evolution as a central component of evolutionary biology. The Network for Experimental Research on Evolution (NERE), a University of California Multicampus Research Program, is our institutional effort to further the same end.

Indeed, experimental evolution is key to the ongoing effort to foster biology's reincarnation as a fully scientific field. It is only when evolutionary histories are known, controlled, and replicated that we can fairly claim to be performing rigorous experimental work. The biology of character X in inbred or mutant strain Y is like a beautiful painting: unique, intriguing, but of uncertain provenance or meaning. Any result with arbitrary strain Y may not be true of other strains or outbred populations of that species. And it will often be unclear how to sort out this situation. Strains M, Q, X, and Z might or might not have the same features. Individual outbred populations are marginally better, because they should have a broader set of genotypes, but they are still unique biological examples, of less reliability than postage stamps that are mass-produced to well-defined standards. If Ernest Rutherford could declare that science can be divided into physics and stamp collecting, then much of biology doesn't even rise to the level of stamp collecting. In its emphasis on hypothesis testing, quantitative trajectories, replication, and reproducibility, experimental evolution resembles physics more than it resembles most research in biology. We can only hope that both Darwin and Rutherford would have approved.

DEFINITIONS AND CONCEPTS

What is *experimental evolution*? We use the term to mean research in which populations are studied across multiple generations under defined and reproducible conditions, whether in the laboratory or in nature (for recent overviews, see Bennett 2003; Garland 2003; Swallow and Garland 2005; Chippindale 2006; Garland and Kelly 2006). This intentionally general definition subsumes various types of experiments that involve evolutionary (cross-generational, genetically based) changes. At one end of the continuum, the study of evolutionary responses to naturally occurring events (e.g., droughts, fires, invasions, epidemics) may constitute a kind of adventitious experimental evolution, especially if these events occur repeatedly and predictably enough that the study can be replicated, either simultaneously or in subsequent years. One might also include "adaptations to the humanized landscape" (Bell 2008b), such as industrial melanism in moths (Clarke 2003). Next, we have "invasive species," which often invade repeatedly, thus allowing study of replicated events (Huey et al. 2005; Gilchrist and Lee 2007; Lee et al. 2007). Intentional "field introductions" involve populations placed in a new habitat in the wild

or cases in which a population's habitat is altered by adding a predator, a pesticide, a food source, fertilizer, and so forth. The experimental population is then monitored across generations and compared with an unmanipulated control population (see Irschick and Reznick this volume).

“Laboratory natural selection” denotes experiments in which the environment of a laboratory-maintained population is altered (e.g., change of temperature, culture medium, food) as compared with an unaltered control population. “Laboratory culling” involves exposing an experimental population to a stress that is lethal (or sublethal) and then allowing the survivors (or the hardiest) to become the parents of the next generation. In all of the foregoing types of experiments, the investigator does not specifically measure and select individuals based on a particular phenotypic trait or combination of traits. Rather, selection is imposed in a general way, and the population has relatively great freedom to respond across multiple levels of biological organization (e.g., via behavior, morphology, physiology). “Multiple solutions” (different adaptive responses among replicate lines) are possible and even probable, depending on the kind of organism and experimental design.

In classical “artificial selection” or “selective breeding” experiments, individuals within a population are scored for one or more specific traits, and then breeders are chosen based on their score (e.g., highest or lowest). Depending on the level of biological organization at which selection is imposed—and the precision with which the phenotype is defined in practice—multiple solutions may again be common (Garland 2003; Swallow et al. this volume).

Domestication is an interesting (and ancient) type of experimental evolution that generally involves some amount of intentional selective breeding. In some cases, the process has been replicated enough times that general principles might be discerned (e.g., several species of rodents have been domesticated). Of course, whenever organisms are brought from the wild to the laboratory or agricultural setting, some amount of adaptation to the new conditions will occur, and this may be studied. Once domesticated, organisms may be the subject of additional selective breeding programs, with varying degrees of control and replication, leading to multiple breeds or lines. Simões et al. (this volume) discuss experimental evolutionary domestication of *Drosophila*.

More recently, the unintentional effects of various actions by human beings have been studied from the perspective that they constitute selective factors whose consequences may be predictable. Examples include changes in commercial fisheries (Hard et al. 2008), sport fishes (Cooke et al. 2007), and various ungulates that are hunted (e.g., Coltman et al. 2003).

What we are terming “experimental evolution” clearly covers a broad range of possible experiments. Historically and at present, different methodologies for experimental evolution have been and are being applied unequally across levels of biological organization (e.g., behavior, life history, physiology, morphology) and across kinds of organisms (e.g., bacteria, *Drosophila*, rodents). For example, experiments in the style of artificial

selection often focus on organismal properties (e.g., physiological performance; see Swallow et al. this volume), whereas studies involving laboratory natural selection tend to focus more on testing genetic or evolutionary principles, with the organism serving perhaps mainly as a convenient conduit to such tests, as has been the case with evolutionary experiments on aging (Rausser et al. this volume) and sex (Turner et al. this volume). Indeed, as noted by one of our reviewers, many of the former types of experiments have their roots in the classic quantitative genetics literature. Of course, many artificial selection experiments have also been motivated by a desire to test aspects of quantitative-genetic theory (Falconer 1992; Hill and Caballero 1992; Bell 2008a, 2008b).

In any case, to qualify as experimental evolution, we require most if not all of the following fundamental design elements: maintenance of control populations, simultaneous replication, observation over multiple generations, and the prospect of detailed genetic analysis. In short, experimental evolution is evolutionary biology in its most empirical guise.

MACROEVOLUTION, MICROEVOLUTION, AND THE ROLE OF SELECTION EXPERIMENTS

The experiments covered in this volume deal with evolving populations. Evolution within populations is traditionally referred to as “microevolution.” The process of speciation (Fry this volume) forms a fuzzy boundary between microevolution and what is termed “macroevolution” (e.g., Charlesworth et al. 1982). Although definitions vary, *macroevolution* is generally used to refer to change at or above the level of the species, including long-term trends and biases that are observed in the fossil record (e.g., see www.talkorigins.org/faqs/macroevolution.html). Macroevolutionary phenomena are difficult to study experimentally because of the long time scales involved. One consequence of this is that many creationists accept microevolution as fact—how could they not if they drink cow’s milk from a modern dairy or eat sweet corn?—but reject the fact of macroevolution.

Experimentally oriented biologists often use microevolutionary analyses to address hypotheses about macroevolution, and this volume includes a number of examples. For example, Swallow et al. (this volume) discuss selection experiments with rodents that are, in part, designed to test hypotheses about the evolution of mammalian endothermic homeothermy. On a seemingly unapproachable level, experimental evolution is now helping us to sort out alternative views about the evolutionary foundations of sex, as shown by Turner et al. (this volume), a process whose origin and evolutionary refinement have no doubt taken hundreds of millions of years.

Attempts to infer something about macroevolution from selection experiments face at least two important challenges. First, the organisms alive today are not the same as those living millions of years ago in which the phenomenon of interest occurred. For example, extant house mice are not the therapsid ancestors of mammals. If mice are

somehow fundamentally different in “construction” from therapsids, then anything learned from experiments with the former may be misleading with respect to the latter. However, interspecific comparative studies (Garland et al. 2005) can be used to establish the generality of various features of organismal “design” and hence to make inferences about what is likely to have been similar versus different between mice (or any other putative model organism) and therapsids.

A second, and perhaps less tractable, limitation of selection experiments for addressing macroevolutionary hypotheses is that they simply may not last long enough to bear witness to all of the things that may have occurred over millions of years, such as the evolutionary consequences of very rare mutational events. For instance, the fixation of novel chromosomal translocations in a eukaryotic population is unlikely to be observed in an experimental evolution study. And is any study in experimental evolution, no matter how cleverly designed, likely to witness an event like the “capture” of a prokaryotic cell by another type of cell that led eventually to eukaryotic mitochondria? Nonetheless, long-term selection experiments (Travisano this volume) will only get longer in the future, and experiments focused on speciation (Fry this volume) and on adaptive radiation (Travisano this volume) have already achieved some notable successes, our caveats notwithstanding. Still, we must accept that mathematical or computer simulation models will need to substitute for, or at least supplement, experimental study of some (macro)evolutionary phenomena (e.g., Gavrillets and Vose 2005; see also Oakley this volume).

OVERVIEW OF THIS VOLUME: EXCLUSIONS AND INCLUSIONS

We have intentionally excluded studies of plants from this volume, in part because fewer such studies exist and in part to keep the size of the volume within reasonable limits. We have also avoided the vast literature on selection experiments in the agricultural world, many of which involve plants (see *Plant Breeding* and *Plant Breeding Reviews*). Comparisons of inbred strains of mice and rats are innumerable (e.g., see *Behavior Genetics*), but they are only mentioned in this volume by Rhodes et al. and Swallow et al.; the latter also make some mention of comparisons of horse and dog breeds.

This volume is divided into five sections. The first includes this introductory chapter, a piece by Futuyma and Bennett that considers the place of experimental studies in evolutionary biology, and an overview of ways to model experimental evolution by Roff and Fairbairn. The second section considers distinguishable types of experimental evolution, ranging from bacteria (Dykhuizen and Dean), domestication (Simões et al.), through long-term experimental evolution, including adaptive radiation (Travisano), experimental studies of reverse evolution (Estes and Teotónio), and field experiments and introductions (Irschick and Reznick).

Part Three covers levels of observation in experimental evolution and includes chapters on fitness, demography, and population dynamics (Mueller), the life-history physiology of insects (Zera and Harshman), behavior and neurobiology (Rhodes and Kawecki),

whole-organism performance and physiology (Swallow et al.), and, finally, genome evolution (Rosenzweig and Sherlock). Our intent in this part of the book is to show how experimental evolution can be used as a broad exploratory spatula with which to separate different horizontal layers of the scientific cake.

Part Four covers some exciting applications of selection experiments and experimental evolution, with reviews of studies that have used phages (Forde and Jessup), a range of organisms to study “allometry” (in the broad sense of the word: Frankino et al.), the evolution of sex (Turner et al.), physiological adaptation in laboratory environments (Gibbs and Gefen), the evolution of aging and late life (Rauser et al.), altruism and the levels of selection (Kerr), speciation (Fry), and experimental phylogenetics (Oakley). Here the field of experimental evolution is sliced up “vertically,” with a diversity of experimental methods being used to address significant problems in evolutionary biology. Although many other useful applications of the techniques of experimental evolution could be included (e.g., fisheries management: Conover and Munch 2002; the evolution of antibiotic resistance: Krist and Showsh 2007), we feel that this miscellany of examples is at least instructive with respect to the scope of this burgeoning literature.

Part Five discusses the difficulties of balancing simplicity and realism in laboratory studies of natural selection, especially when they are intended to simulate selection in the wild (Oakley; Huey and Rosenzweig).

SUMMARY

Experimental evolution is becoming a mainstream part of the biological sciences, beyond the confines of evolutionary biology, narrowly construed. For example, the journal *Integrative and Comparative Biology* recently published a symposium on “Selection Experiments as a Tool in Evolutionary and Comparative Physiology: Insights into Complex Traits” (Swallow and Garland 2005). In 2007, the journal *Physiological and Biochemical Zoology* published a “Focused Issue” on “Experimental Evolution and Artificial Selection.” The response to the call for papers was so great that they ended up publishing papers in parts of three successive issues, including several by contributors to this volume. In 2008, the journal *Heredity* published a collection of six short reviews on microbial studies using experimental evolution (Bell 2008a). And experimental evolution is making it into the curriculum (e.g., box 13.3 in Moyes and Schulte 2006; Krist and Showsh 2007).

This volume provides further evidence that selection experiments have arrived. We hope that it serves to stimulate experimental evolutionary studies broadly. We also hope that it helps to improve the nature of such studies by careful attention to experimental design. In closing, we would appeal to the words of our colleagues regarding the importance of selection experiments and experimental evolution:

Ultimately, laboratory systems provide the best opportunity for the study of natural selection, genetic variation, and evolutionary response in the same population. . . . We

suggest that the study of natural selection in a laboratory setting is the best method of making the link between natural selection and evolution and may thus permit predictive and rigorous study of adaptation. Houle and Rowe (2003, 50–51).

Selection experiments are irreplaceable tools for answering questions about adaptation and the genetic basis of adaptive trait clusters (i.e., repeated evolution of suites of traits in particular environments). (Fuller et al. 2005, 391)

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