

Darwin and species

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ONE WOULD HAVE thought that, by now, 150 years after the *Origin*, biologists could agree on a single definition of species. Many biologists had indeed begun to settle on the “biological species concept” in the late modern synthesis (1940–70), when new findings in genetics became integrated into evolutionary biology. However, the consensus was short-lived. From the 1980s until the present, it seems not unfair to say that there arose more disagreement than ever before about what species are. How did we get into this situation? And what does it have to do with Darwin? Here, I argue that a series of historical misunderstandings of Darwin’s statements in the *Origin* contributed at least in part to the saga of conflict among biologists about species that has yet to be resolved. Today, Darwinian ideas about species are becoming better understood. At long last, the outlines of a new and more robust Darwinian synthesis are becoming evident. This “resynthesis” (as it perhaps should be called) mixes Darwin’s original evolutionary ideas about species with evidence from modern molecular and population genetics.

WHAT DID DARWIN MEAN BY SPECIES?

Darwin realized he had convincing proof that species were not created but evolved. But this understanding caused a terminological problem that he had to address in his book. Species were defined in the minds of many of his Creation-educated readers as members of real groups: all members of a species were related by descent, whereas no individual was descended from members of another species. A second idea, which had been promoted especially by the French naturalist Buffon, was that the intersterility of species was a protective mechanism with which species had been endowed by the Creator to maintain their purity (Fig. 11.1). Thus, the famous anatomist Richard Owen, a powerful creationist opponent of Darwin, had given this succinct definition in his 1858 treatise on chimpanzees and orangutans: “an originally distinct creation, maintaining its primitive distinction by obstructive generative peculiarities” (as cited by Huxley 1860, 544).

In order that he could make the argument that species evolved under his theory of “descent with modification,” Darwin required a new definition of species. In



FIGURE 11.1. Georges-Louis Leclerc, comte de Buffon (1707–88), one of the leading naturalists of the eighteenth century and suspected of having transformist yearnings. Permission: Wellcome

particular, descent must now be allowed to extend not only within species but also across the species boundary, and ultimately to encompass all living things. Common descent could no longer be used simply as a definition of species. If species evolved, we would also expect hybrid sterility to show evidence of continuous evolution across the species boundary. This terminological problem about species did not, apparently, trouble Darwin greatly (except for the matter of hybrid sterility), and he spent only a little space discussing what he meant by species. Perhaps, as a naturalist, he thought that the existence and nature of species would be self-evident to his readers. Even in later editions of the *Origin*, to which he added a glossary, there is no formal definition of species.

Nonetheless, Darwin did, in my view, clearly indicate what he meant by species, and the conception of species in the *Origin* is now generally recognized by philosophers and historians to have been a useful one for his purpose – that is, to demonstrate evidence for their transmutation (A. O. Lovejoy 1959; Ghiselin 1969; Kottler 1978; Beatty 1985; Ruse 1987; McOuat 1996; Stamos 2006; Kohn 2009; Sloan 2009; Ereshefsky 2010a). Darwin’s definition was the simplest that allowed for multiple species to originate from a single ancestral species. One of his clearest short statements on species is in the summary at the end of the *Origin*: “Hereafter we shall be compelled to acknowledge that the only distinction between species and well-marked varieties is, that the latter are known, or believed, to be connected at the present day by intermediate gradations, whereas species were formerly thus connected” (Darwin 1859, 485).

In the *Origin*, Darwin devoted a large portion of chapter 2 (“Variation under Nature”) to discussing what species and varieties were, and how difficult they can be to distinguish: “Practically, when a naturalist can unite two forms together by others having intermediate characters, he treats the one as a variety of the other, ranking the most common, but sometimes the one first described, as the species, and the other

as the variety” (1859, 47). Of course, it is really a statement about varieties, not species: forms lacking morphological gaps between them are varieties; but a species definition is implicit: forms that have gaps between them are separate species.

But then Darwin immediately qualified this statement and, in doing so, unwittingly confused many of his subsequent readers: “But cases of great difficulty, which I will not here enumerate, sometimes occur. . . . Hence, in determining whether a form should be ranked as a species or a variety, the opinion of naturalists having sound judgement and wide experience seems the only guide to follow” (47). Many subsequent authors have cited the latter sentence as evidence of Darwin’s nihilism about species, while ignoring the foregoing statements. In fact, if the unwary reader fails to concentrate, Darwin seems to tack back and forth, with statements such as: “To sum up, I believe that species come to be tolerably well-defined objects, and do not at any one period present an inextricable chaos of varying and intermediate links” (177), which sounds almost like the opposite of what he has said in chapter 2.

Later, in *The Descent of Man* (Darwin 1871a), there is perhaps a rather clearer statement: “Independently of blending from intercrossing, the complete absence, in a well-investigated region, of varieties linking together any two closely-allied forms, is probably the most important of all the criterions of their specific distinctness.” Darwin used this definition to argue that all of the races of Man belong to the same species (1:214–15).¹

It seems quite clear to me, even from the few excerpts cited here, that Darwin never claimed that species did not exist or were “unreal,” however many biologists, philosophers of science, and historians of science would have us believe the converse (a more detailed textual analysis is given in Mallet 2010b). Darwin was not arguing that all species are arbitrary. The statement “the opinion of naturalists having sound judgement and wide experience seems the only guide to follow” did not imply that “naturalists of sound mind” were required to use educated guesswork. Darwin was certainly arguing that species were similar to “varieties” but only up to a point. Species differed from varieties in that they lacked morphological intermediates: there were gaps between them. In his view, Darwin had indicated adequately what he meant by species and then moved on. A more important task, and a major one in the *Origin*, was to show that there were many fuzzy borderline cases – these provided evidence for continuous evolution between species.

¹ Darwin’s bitter opponent Richard Owen (1859), while deprecating the idea that humans evolved from apelike ancestors, nonetheless categorized species the same way as Darwin did: that all human races belonged to the same species, whereas the orang, chimpanzee, and gorilla were separate species. He did this for very much the same anatomical and morphological reasons as Darwin did – the presence or absence of intermediates. The last thing that Darwin would have wanted was to invent a definition of species that played havoc with existing taxonomy. In the *Origin* he needed only to explain how generally accepted taxonomic species, those recognized by “naturalists having sound judgement,” could have evolved. He intentionally adopted the practical methods that most naturalists were using in 1859, while separating his definition of species from the creationist baggage it had carried hitherto.

Good evidence for this interpretation is that the pages containing Darwin's most disputed passages about species in chapter 2 all have the header "DOUBTFUL SPECIES" in the first edition (Mallet 2010b). Darwin was merely showing here that, in *doubtful* cases, it is difficult to tell species from varieties, as a necessary prelude to arguments about how species might evolve. He never intended the message, now widely believed to be Darwin's goal by latter-day readers, that *all* species blended together "in an inextricable chaos of varying and intermediate links."

THE MYTH OF "DARWIN'S FAILURE"

It is an extraordinary paradox that what to Darwin was the most important theme of the *Origin* also became the most doubtful in the minds of his readers, even today. Almost everybody, at least by the mid-twentieth century, agreed that Darwin had written a great book, that he had proved that species had evolved from varieties, and that natural selection was an important process in nature. What they found increasingly hard to accept, however, was that Darwin had understood what species were and had made any effort to explain the origin species from varieties or that natural selection was involved (Mallet 2008). By the time of the "modern synthesis," this view hardened into a dogma that Darwin had completely failed:

Darwin succeeded in convincing the world of the occurrence of evolution and ... he found (in natural selection) the mechanism that is responsible for evolutionary change and adaptation. It is not nearly so widely recognized that Darwin failed to solve the problem indicated by the title of his work. Although he demonstrated the modification of species in the time dimension, he never seriously attempted a rigorous analysis of the problem of the multiplication of species, the splitting of one species into two. (Mayr 1963, 12)

In retrospect, it is apparent that Darwin's failure ... resulted to a large extent from a misunderstanding of the true nature of species. (Mayr 1963, 14).

Ernst Mayr's critique came from the modern synthesis standpoint of his own "biological species concept," in which species were defined as populations reproductively isolated from one another by "reproductive isolating mechanisms" (Plate XVIII). Darwin, argued Mayr, had not understood the fundamental importance of reproductive isolation in speciation implied by the biological species concept. The undoubted primary reason why Mayr found Darwin's pronouncements on species illogical was that Darwin strenuously argued in his chapter "Hybridism" against the importance of hybrid sterility in providing either a useful definition of species or an explanation of speciation: "It can thus be shown that neither sterility nor fertility affords any certain distinction between species and varieties" (Darwin 1859, 248). To Mayr, in contrast, hybrid sterility and other "isolating mechanisms" were the key differences between species and varieties, and the elucidation of their origin constituted an understanding of speciation. Mayr's isolating mechanism of hybrid sterility

was to Darwin an incidental by-product of other evolutionary changes between species, that would not have warranted the term "mechanism" at all, because it could not be explained directly by natural selection.² Darwin certainly appreciated how species intersterility and reluctance to mate allowed the coexistence of species and discussed that these traits were strongly associated with what taxonomists recognized as separate species (Mallet 2010b). Yet to Darwin it was the failure of direct natural selection to explain the evolution of hybrid sterility, the fertility of many hybrids between "good species," and the existence of some kinds of infertility within species that forced him to abandon an idea that species could be defined via reproductive isolation.

However, let us not just blame Mayr and the modern synthesis for this misunderstanding. The problems for understanding Darwin's ideas about species go back much further than the middle of the twentieth century. The seeds of the difficulty can be seen even in one of the most positive reviews ever published of the *Origin*, by the very man nicknamed "Darwin's bulldog," Thomas Henry Huxley. While generally complimentary about natural selection and the claim that species arose by evolution, he also wrote, "There is no positive evidence, at present, that any group of animals has, by variation and selective breeding, given rise to another group which was even in the least degree, infertile with the first. Mr. Darwin is perfectly aware of this weak point, and brings forward a multitude of ingenious and important arguments to diminish the force of the objection... but still, as the case stands, this 'little rift in the lute' is not to be disguised or overlooked" (Huxley 1860, 309). This statement forms a conclusion to a long discussion of Darwin's evidence on the nature of species, with which Huxley largely agrees.

But the "rift in the lute" turned out (and was perhaps intended) to be a very British understatement. Wallace (1889, 152) wrote that it was "one of the greatest, or perhaps we may say the greatest, of all the difficulties in the way of accepting the theory of natural selection as a complete explanation of the origin of species." Much later, "the remarkable difference between varieties and species with respect to fertility when crossed" was seen by a major twentieth-century historian of evolutionary ideas as one of the six major difficulties for the acceptance of Darwinian evolution (A. O. Lovejoy 1959).³

² Mayr, unlike Dobzhansky, agreed with Darwin that there was no evidence that sterility and inviability had evolved via natural selection. Nonetheless, he clearly agreed with Dobzhansky that isolating mechanisms were in some sense adaptive, that they were useful to species as a means of keeping them apart from other species (Mallet 2010a).

³ This paper was originally published for the first Darwin centenary in 1909 and revised for the centenary of the *Origin* in 1959. To my mind, it remains one of the best pieces of scholarship documenting not only precisely what it was that Darwin and Wallace discovered but also the great mystery of why other biologists such as Thomas Henry Huxley did not discover it, even though many of Darwin's conclusions in retrospect immediately seemed quite obvious. As Huxley (1887, 2:197) himself remarked: "My reflection, when I first made myself master of the central idea of the 'Origin' was, 'How extremely stupid not to have thought of that!'"

The problem arises with the second part of Owen's definition "maintaining its primitive distinction by obstructive generative peculiarities." Darwin had argued vehemently against reproductive isolation as a definition of species because creationists, from Buffon onward, had proposed hybrid sterility to be evidence of the Creator's wisdom. Darwin probably felt he had to show that sterility was not, in fact, a valid definition in order to disabuse his readership of the idea. But to those, like Owen and Huxley, for whom it was key to explain hybrid sterility in a theory of speciation, Darwin's belittling of its importance seemed to duck the issue, while his partial explanation seemed weak. Darwin was very clear that his greatest theory, natural selection, failed to explain hybrid sterility. What then caused it? "The foregoing rules and facts ... appear to me clearly to indicate that the sterility, both of the first crosses and of hybrids is simply incidental or dependent on unknown differences, chiefly in the reproductive systems, of the species which are crossed. The differences being of so peculiar and limited a nature, that in reciprocal crosses between two species the male sexual element in one will often freely act on the female sexual element of the other, but not in reversed direction" (1859, 260–61); "sterility of first crosses and of hybrids ... is not a special endowment, but is incidental on slowly acquired modifications, more especially in the reproductive systems of the forms which are crossed" (272)

In other words, Darwin did not know what caused hybrid sterility, although some causes could be ruled out. However, hybrid sterility was far from universal among species and was so scattered and "incidental" that it seemed most unlikely that it was either a naturally selected adaptation or an attribute provided by God to preserve the purity of species. It must instead be "incidental on slowly acquired modifications" – a by-product of evolutionary divergence in general – or a "pleiotropy," to use today's genetic term. Evidence in correspondence from Darwin to Wallace in 1868 indicates that Darwin himself was dissatisfied with his partial explanation, although it was clearly more of a problem for Huxley and others. Today, whatever their view of Darwin's ideas about speciation, evolutionary biologists accept Darwin's opinion that hybrid sterility is not an adaptation. With hindsight, I believe we can forgive Darwin for not explaining sterility: it is only now that its precise causes are becoming understood. Sterility represents a failure in hybrids of normal beneficial interactions among genes that have diverged in different populations for a sufficiently long time. Although such genes are often popularly referred to as "speciation genes," it is now generally recognized that many differences, and probably most of them, that cause negative interactions in hybrids evolved long after speciation is complete and rarely, if ever, cause species to divide (Coyne and Orr 2004; H. A. Orr 2009).

PHYSIOLOGICAL SPECIES VERSUS MORPHOLOGICAL SPECIES

Huxley argued that Darwin's use of the term "species" was indeed useful but that it was based only on morphology. But

to Huxley, another very important difference between species was what he called "physiological." "Physiological species" are those that are unable to interbreed successfully (Huxley 1860, 296). It is not entirely clear whether Huxley invented the term "physiological species," which does not appear in Darwin's writings, or whether he co-opted it from other sources that were generally read then. Regardless of the source of the idea, "physiological species" became a touchstone for an argument that dogged evolutionary biology for the next 150 years. A preference for physiological species over Darwinian morphological species was also the major reason for the later rejection of the Darwinian notion of species, as well as of their origin.

Henry Walter Bates, writing in 1863 about *Heliconius* butterflies, alluded, one assumes, to Huxley's critique of the *Origin* in the following terms: "In the controversy which is being waged among Naturalists, since the publication of the Darwinian theory of the origin of species, it has been rightly said that no proof at present existed of the production of a physiological species, – that is, a form which will not interbreed with the one from which it was derived, although given ample opportunities of doing so, and does not exhibit signs of reverting to its parent form when placed under the same conditions with it." Bates argued that his study of *Heliconius* butterflies in Brazil did, however, "tend to show that a physiological species can be and is produced in nature out of the varieties of a pre-existing closely allied one." Bates purported to show that although *Heliconius melpomene* and *H. thelixiope* hybridize in some places, they also "come into contact in several places where these intermediate examples are unknown, and I never observed them to pair with each other" (Bates 1863, 1:256–62). While today's taxonomy does not, I believe, support Bates's argument in the case of *Heliconius*, this passage clearly shows that Huxley's critique and the need to explain "physiological species" were a topic of discussion at the time.

In his own apparent response to Huxley, Darwin's conception of species (1871a, 214–15) added a physiological dimension: "In determining whether two or more allied forms ought to be ranked as species or varieties, naturalists are practically guided by ... the amount of difference between them, and whether such differences relate to few or many points of structure, and whether they are of physiological importance. ... Even a slight degree of sterility between any two forms when first crossed, or in their offspring, is generally considered as a decisive test of their specific distinctness." This added to but did not preclude Darwin's morphological gap argument, still voiced in the same pages (see above).

In March and April 1868, Alfred Russel Wallace and Charles Darwin corresponded extensively on the subject of hybrid sterility. Wallace asked Darwin whether he could imagine that hybrid sterility arose through natural selection and suggested several possible schemes. Darwin, perhaps exhausted by Wallace's youthful enthusiasm, enlisted his more mathematical son George (then at Cambridge) to help; together they rebutted Wallace's arguments. Darwin wrote



FIGURE 11.2. George J. Romanes (1848–94) was a very enthusiastic disciple of Darwin. From Mrs. Romanes, *Life and Letters of George John Romanes* (London: Longmans, Green, 1896)

back to a second enquiry: “Let me first say that no man could have more earnestly wished for the success of N. selection in regard to sterility, than I did; & when I considered a general statement, (as in your last note) I always felt sure it could be worked out, but always failed in detail. The cause being as I believe, that natural selection cannot effect what is not good for the individual” (Darwin 1985–, 16:374, letter to Wallace, 6 April 1868). Wallace did, however, touch upon one likely argument that Darwin could not refute, that “disinclination to cross” could be effected by natural selection. Darwin again: “I know of no ghost of a fact supporting belief that disinclination to cross accompanies sterility. It cannot hold with plants, or the lower fixed aquatic animals. I saw clearly what an immense aid this would be, but gave it up. Disinclination to cross seems to have been independently acquired probably by nat. selection; & I do not see why it would not have sufficed to have prevented incipient species from blending to have simply increased sexual disinclination to cross.”

Wallace wrote back: “I am sorry you should have given yourself the trouble to answer my ideas on Sterility – If you are not convinced, I have little doubt but that I am wrong; and in fact I was only half-convinced by my own arguments, – and

I now think there is about an even chance that Nat. Select. may or not be able to accumulate sterility.” Prophetically, he ended the discussion with a prediction that, even so, it would be a source of controversy: “However I will say no more but leave the problem as insoluble, only fearing that it will become a formidable weapon in the hands of the enemies of Nat. Selection” (Darwin 1985–, 16:389, letter from Wallace to Darwin, 8 April 1868). As it turned out, this problem led to opposition also from within the ranks of those who called themselves Darwinists.

In 1886 George Romanes, a correspondent and self-avowed “close student” of Darwin’s, published a long and discursive paper to suggest a supposedly new mechanism of how Huxley’s physiological species separated by hybrid sterility could come into being, a process he called “physiological selection” (Fig. 11.2). Romanes (1886, 370–71) argued that natural selection was incompetent to cause species to diverge: “The theory of natural selection is not, properly speaking, a theory of the origin of species: it is a theory of the development of adaptive structures. . . . What we require in a theory of the origin of species is a theory to explain [the origin of] the primary and most constant distinction between species . . .[:] comparative sterility towards allied forms, with continued fertility within the varietal form.”

Romanes agreed with another Darwin critic (Wagner 1868, 1873) that if populations were geographically isolated, divergent variations would not be swamped by intercrossing and so could diverge to form separate species. However, Romanes did not believe that all speciation could be due to geographical isolation; physiological selection, in his view could have the same effect of preventing gene flow. According to Romanes (1886, 370–71), if a variation (or mutation) occurs but has no effect within an emerging variety, “such that the reproductive system, while showing some degree of sterility with the parent form, continues to be fertile within the limits of the varietal form, in this case the variation would neither be swamped by intercrossing, nor would it die out on account of sterility. On the contrary, the variation would be perpetuated with more certainty than could a variation of any other kind.”

Wallace (1886), recognizing the similarity of “physiological selection” to earlier ideas he had himself communicated to Darwin for the evolution of intersterility by means of natural selection, wrote a number of articles rebutting Romanes’ suggestions. He returned to the theme in his major work intended to update and promote Darwinism thirty years after the *Origin* (Wallace 1889). Perhaps his most cogent criticism was that Romanes had merely asserted the importance of physiological selection (clearly evident also from the Romanes quotation reproduced in the preceding paragraph); he had failed to propose a convincing mechanism whereby it would occur or to provide any empirical evidence for its operation. Wallace (1889, 181–83) introduced a mathematical argument to show that Romanes’ assertion did not work, showing that eventually a new and scarcer variety that produced infertile hybrids with the commoner “wild-type” would die out. The argument

assumes complete hybrid sterility but works as well with partial sterility.

Nonetheless, Wallace himself reiterated his 1868 ideas in a lengthy and rather diffuse section of nearly 1,800 words earlier in the same chapter. He argued that hybrid sterility could be explained by means of natural selection. This passage is today difficult to interpret, and, as if anticipating the befuddlement of his readers, Wallace used a still rather lengthy footnote (about 850 words) to elaborate a “briefer exposition . . . , in a series of propositions.” These propositions were almost identical to those in his 1868 letter to Darwin.

Wallace’s (1889, 175–78) first idea was that hybrid sterility might arise “in correlation with the different modes of life and the slight external or internal peculiarities that exist between them.” If so, sterility would be a by-product of the divergent environments or inherited adaptive change of two emerging varieties and could be stable to swamping. This can be interpreted in today’s terms as a pleiotropy argument: a selective adaptation to conditions of life can evolve that outweighs the indirect or pleiotropic disadvantage of the negative side effects of the same genes on hybrid sterility. Wallace essentially reiterated Darwin’s (1859) hypothesis for the evolution of hybrid sterility, and this is the one most strongly supported today.

Wallace’s second, and major argument for the evolution of sterility should probably be interpreted as a kind of selection on groups rather than Darwinian natural selection on individuals. If in one part of the range of a species, diverging into two varieties under natural selection, hybrids happened to be more sterile, while in another part hybrids among the same two emerging varieties were somewhat less sterile, Wallace (1889, 175) claimed that forms showing greater hybrid sterility would increase more rapidly as a result of their greater genetic purity owing to better adaptation to conditions causing the emergence of the divergent varieties in the first place. This is a tricky argument to make, as it is directly contradicted within each region by the very same Darwinian argument that he used against Romanes, outlined later in the same chapter. It relies on the idea that populations with higher sterility leave more offspring overall (because of the greater purity and better adaptation to local conditions) than populations with lower sterility (and therefore lower purity). Biologists today accept that situations under which interpopulation selection or group selection of this kind outweighs a countervailing force of natural selection within populations will be rare. If we view sterility for what it is, a problem for the individual, we can imagine that sometimes a beneficial adaptation that also causes sterility will evolve *in spite of* sterility, because the benefits of the adaptation outweigh the loss of offspring. This could lead to greater hybrid sterility as a by-product (Wallace’s first hypothesis). But by arguing for hybrid sterility as a direct potential advantage for populations, I think that it is correct to say (Kottler 1985; N. A. Johnson 2008) that Wallace was falling into the trap of naïve group selectionism (D. S. Wilson and E. O. Wilson 2007).

A third suggestion by Wallace, again following on from the earlier correspondence with Darwin, was that new varieties would show a correlated “disinclination to pair.” Wallace (1889, 172–73, 175–76) argued here that adaptation to different modes of life would also bring about a reduction in tendency to pair between divergent varieties, perhaps simply because organisms specializing in different resources met less often. Darwin, as we have seen, argued that there was no evidence for this. In modern terms, this is arguing for what has been lightheartedly termed a “magic trait” – that is, a pleiotropic effect that automatically aids speciation (Gavrilets 2004). Pleiotropic effects of ecological adaptation on mate choice are today thought to provide an important route to ecological speciation (Drès and Mallet 2002; Hendry, Nosil, and Rieseberg 2007).

There is a fourth and final suggestion, which Wallace could have made in 1868 or 1889 but apparently did not. As Darwin had briefly mentioned in his letter of reply to Wallace, “disinclination to pair” with individuals of a different type would seem likely to be enhanced by natural selection because it would reduce the number of useless offspring that might become sterile. This argument was revived again by Theodosius Dobzhansky in 1940 and became variously known as “reinforcement” (Blair 1955; Levin 1970; Butlin 1985), or the “Wallace effect” (Grant 1966; Murray 1972). Today reinforcement is generally accepted as a possibly common means whereby reproductive isolation is acquired via natural selection (Coyne and Orr 2004; N.A. Johnson 2008).

POST-MENDELIAN IDEAS OF PHYSIOLOGICAL SPECIES

By around the turn of the century, many people were again beginning to argue, in contrast to Darwin and Wallace, that species should be defined physiologically – that is, by means of their reproductive isolation (Cockerell 1897; Petersen 1903; Poulton 1904; K. Jordan 1905). With the rediscovery of Mendelian heredity, William Bateson and the Mendelians approached the understanding of species from a new, experimental genetics viewpoint; sterility could now be investigated in the laboratory. Bateson reiterated the argument that Darwin’s definition of species ignored their most important feature, their physiological tendency to produce sterile hybrids (W. Bateson 1913, 1922). Darwin’s was an incomplete theory of speciation because it could not explain this important “specificity” of species in nature, as Bateson called it. By 1926, the Russian geneticist Sergei Chetverikov had argued that “the real source of speciation, the real cause of the origin of species is not selection, but [reproductive] isolation” (quoted in Krementsov 1994, 41).

Russian entomologists and geneticists such as Wilhelm Petersen, Sergei Chetverikov, and A. P. Semenov-Tian-Shanskii, as well as workers in the United States and Europe, who all supported these new ideas on species, were undoubtedly strong influences on the young entomologist and later geneticist Theodosius Dobzhansky (Krementsov 1994). After

emigrating to the United States, Dobzhansky wrote the most widely read treatise of this period on the origin of species. This work blended genetic and Darwinian ideas about speciation for the first time and supported the idea of species being definable via “physiological isolating mechanisms”: “When such mechanisms have developed [between two diverging races], and the prevention of interbreeding is more or less complete, we are dealing with separate species” (Dobzhansky 1937, 63).

In an important section, “The Origin of Isolation,” Dobzhansky argued that hybrid sterility and sexual or psychological isolation could reinforce one another, and that further isolation could in some circumstances be adaptive. As applied to hybrid sterility and inviability, this again appears to be an example of naïve group selectionism (see especially 257–58), even though in the same chapter he also accepted Darwin’s argument that hybrid sterility was often a by-product of divergent evolution rather than a directly selected influence on speciation. Dobzhansky was promoting a Darwinian approach to the understanding of speciation, and he seems to have been careful to avoid a direct critique of Darwin’s own view of species, which of course differed from his own.

Ernst Mayr (1942, 1963) adopted Dobzhansky’s reproductive isolation definition of species, and renamed it “the biological species concept.” As we have seen, he did not shy away from arguing that this “new” idea of species was very different from Darwin’s and that it demanded an entirely new view of the origin of species. In the opinion of Dobzhansky and Mayr, this new view of species and speciation represented the modern synthesis of Darwinism and Mendelian genetics.

SPECIES CONCEPTS TODAY

We have seen how Darwin failed to convince Huxley, his chief supporter, that it was best not to define species via reproductive isolation. Huxley’s invention of the term “physiological species” led first to a resurgence and finally, by the 1960s, an almost complete acceptance of the idea that the fundamental nature of species was reproductive isolation – the very idea that Darwin had tried to disprove. Given that opinions about the importance of reproductive isolation differed, this treatment of species as if they were fundamentally and physiologically distinct from varieties led to a search for alternative fundamental concepts to define species. According to one concept, a phylogenetic species is a distinct form that retains stable morphological or genetic differences, whether or not it is reproductively isolated (Cracraft 1989). A recent version of this idea employs Bayesian statistical analyses of genealogical coalescence to determine the presence of separate, phylogenetic species in a set of individual genomic sequence data. Under this idea of species, one must infer from the genetic data at least a minimal time of separation between a pair of populations to classify them as separate species (Yang and Rannala 2010).

THE VALIDITY OF A DARWINIAN NOTION OF SPECIES IN 2013

Another view, however, is that a Darwinian delimitation of species still today has validity: species are separate “genotypic clusters” when considered in a molecular genetic sense (Mallet 1995). Arguing for two species on the basis of genetic data is equivalent to arguing that there are two sets of individuals each coming from a population with gene frequencies that may differ. In other words, one needs only to disprove the null hypothesis that there is a single population in the array of individual genetic or genomic data in order to prove that the presence of two populations is a better hypothesis; and the method can be extended to multiple populations. If we plot the distribution of individuals along axes representing multilocus gene frequencies, the distribution will be bimodal if there are two species, or single peaked if there is only one. Data can be treated statistically by means of a Bayesian Markov-Chain Monte-Carlo approach (Pritchard, Stephens, and Donnelly 2000; Huelsenbeck and Andolfatto 2007). This procedure is called an “assignment test” because it determines the appropriate number of distinct populations into which to assign each of the genotyped individuals in a sample.

Gene frequencies may of course differ if populations are spatially isolated without necessarily implying speciation, but if distinguishable populations occur together in the same region and yet retain differences at multiple loci, the two populations will generally be accepted to be different species. Intermediates (or hybrids) may occur, but provided they are rare in areas of overlap, these populations can be considered separately delimited species.

Assignment tests are useful in delimiting cryptic species in many groups, such as flowering plants (Larson et al. 2010; Zeng et al. 2010), corals (Pinzón and Lajeunesse 2011), butterflies (Dasmahapatra et al. 2010), or primates such as mouse lemurs (Weisrock et al. 2010). These methods are also useful for identifying genetically distinguishable ecological taxa normally considered below the species level in taxa such as aphids (Peccoud et al. 2009) or social-group forms of mammals such as the orca (killer whale) (Hoelzel et al. 2007). In Darwinian terms, such ecological races represent exactly the “doubtful cases” that Darwin used to suggest that species evolved from varieties.

Today, it seems, we have come full circle from a general disregard for Darwin’s view of species to using statistical methods employing a recognizable Darwinian notion of species, although today’s methods tend to use genetic rather than purely morphological data. Physiological and biological concepts of species can be seen as explanations for the scarcity of intermediates between species, and so genotypic bimodality makes as much practical sense to those who support phylogenetic or biological concepts of species as it does to those who feel that Darwin was correct about species all along. Perhaps now “we shall at least be freed from the vain search for the undiscovered and undiscoverable essence of the term species” (Darwin 1859, 485). We shall see.

References

- Bates HW. 1863.** *A Naturalist on the River Amazons*. London: John Murray.
- Bateson W. 1913.** *Problems of Genetics*. New Haven, Connecticut: Yale University Press.
- Bateson W. 1922.** Evolutionary faith and modern doubts. *Science* **55**: 55-61.
- Beatty J. 1985.** Speaking of species: Darwin's strategy. In: Kohn D, ed. *The Darwinian Heritage*. Princeton, NJ: Princeton Univ. Press, 265-281.
- Blair WF. 1955.** Mating call and stage of speciation in the *Microhyla olivacea* - *M. carolinensis* complex. *Evolution* **9**: 469-480.
- Butlin RK. 1985.** Speciation by reinforcement. In: Gosálvez J, ed. *Orthoptera*. Madrid: Fundación Ramón Areces, 84-113.
- Cockerell TDA. 1897.** "Physiological species". *Entomological News* **8**: 234-236.
- Coyne JA, Orr HA. 2004.** *Speciation*. Sunderland, Mass.: Sinauer Associates.
- Cracraft J. 1989.** Speciation and its ontology: the empirical consequences of alternative species concepts for understanding patterns and processes of differentiation. In: Otte D, Endler JA, eds. *Speciation and its Consequences*. Sunderland, Mass.: Sinauer Associates, 28-59.
- Darwin CR. 1859.** *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life*. London: John Murray.
- Darwin CR. 1871.** *The Descent of Man, and Selection in Relation to Sex*. London: John Murray.
- Dasmahapatra KK, Elias M, Hill RI, Hoffmann JI, Mallet J. 2010.** Mitochondrial DNA barcoding detects some species that are real, and some that are not. *Molecular Ecology Resources* **10**: 264-273.
- Dobzhansky T. 1937.** *Genetics and the Origin of Species*. New York: Columbia Univ. Press.
- Drès M, Mallet J. 2002.** Host races in plant-feeding insects and their importance in sympatric speciation. *Philosophical Transactions of the Royal Society of London Series B-Biological Sciences* **357**: 471-492.
- Ereshefsky M. 2009.** Darwin's solution to the species problem. *Synthèse* **xxx**: 000.
- Gavrilets S. 2004.** *Fitness Landscapes and the Origin of Species*. Princeton: Princeton University Press.

- Ghiselin MT. 1969.** *The Triumph of the Darwinian Method*. Berkeley: Univ. California Press.
- Grant V. 1966.** The selective origin of incompatibility barriers in the plant genus, *Gilia*. *American Naturalist* **100**: 99-118.
- Hendry AP, Nosil P, Rieseberg LH. 2007.** The speed of ecological speciation. *Functional Ecology* **21**: 455-464.
- Hoelzel AR, Hey J, Dahlheim ME, Nicholson C, Burkanov V, Black N. 2007.** Evolution of population structure in a highly social top predator, the killer whale. *Molecular Biology and Evolution* **24**: 1407-1415.
- Huelsenbeck JP, Andolfatto P. 2007.** Inference of population structure under a Dirichlet process model. *Genetics* **175**: 1787-1802.
- Huxley TH. 1860.** Darwin on the origin of species. *Westminster Review* n.s. **17**: 541-570.
- Huxley TH. 1887.** On the reception of the 'Origin of Species'. In: Darwin F, ed. *The Life and Letters of Charles Darwin. Including an Autobiographical Chapter. Edited by his Son. Volume 2*. London: John Murray, 179-204.
- Johnson NA. 2008.** Direct selection for reproductive isolation: the Wallace effect. In: Smith CH, Beccaloni G, eds. *Natural Selection and Beyond: The Intellectual Legacy of Alfred Russell Wallace*. Oxford: Oxford University Press, 114-124.
- Jordan K. 1905.** Der Gegensatz zwischen geographischer und nichtgeographischer Variation. *Zeitschrift für Wissenschaftliche Zoologie* **83**: 151-210.
- Kohn D. 2009.** Darwin's keystone: the principle of divergence. In: Richards RJ, Ruse M, eds. *The Cambridge Companion to the Origin of Species*. Cambridge: Cambridge University Press, 87-108.
- Kottler MJ. 1978.** Charles Darwin's biological species concept and the theory of geographical speciation. The transmutation notebooks. *Annals of Science* **35**: 275-297.
- Kottler MJ. 1985.** Charles Darwin and Alfred Russel Wallace: two decades of debate over natural selection. In: Kohn D, ed. *The Darwinian Heritage*. Princeton, N.J.: Princeton University Press, 367-432.
- Krementsov NL. 1994.** Dobzhansky and Russian entomology: the origin of his ideas on species and speciation. In: Adams MB, ed. *The Evolution of Theodosius Dobzhansky*. Princeton, New Jersey: Princeton Univ. Press, 31-48.
- Larson SR, Culumber CM, Schweigert RN, Chatterton NJ. 2010.** Species delimitation tests of endemic *Lepidium papilliferum* and identification of other possible evolutionarily significant units in the *Lepidium montanum* complex (Brassicaceae) of western North America. *Conservation Genetics* **11**: 57-76.

- Levin DA. 1970.** Reinforcement of reproductive isolation: plants versus animals. *American Naturalist* **104**: 571-581.
- Lovejoy AO. 1968.** The argument for organic evolution before *The Origin of Species*, 1830-1858. In: Glass B, Temkin O, Straus WL, eds. *Forerunners of Darwin: 1745-1859*. Baltimore, Maryland: Johns Hopkins Press, 356-414.
- Mallet J. 1995.** A species definition for the Modern Synthesis. *Trends in Ecology and Evolution* **10**: 294-299.
- Mallet J. 2008a.** Hybridization, ecological races, and the nature of species: empirical evidence for the ease of speciation. *Philosophical Transactions of the Royal Society B-Biological Sciences* **363**: 2971-2986.
- Mallet J. 2008b.** Mayr's view of Darwin: was Darwin wrong about speciation? *Biological Journal of the Linnean Society* **95**: 3-16.
- Mallet J. 2010a.** Group selection and the development of the biological species concept. *Philosophical Transactions of the Royal Society B-Biological Sciences* **365**: 1853-1863.
- Mallet J. 2010b.** Why was Darwin's view of species rejected by 20th Century biologists? *Biology and Philosophy* **25**: 497-527.
- Mayr E. 1963.** *Animal Species and Evolution*. Cambridge, Mass.: Harvard University Press.
- McOuat GR. 1996.** Species, rules and meaning: the politics of language and the ends of definitions in 19th Century natural history. *Studies in History and Philosophy of Science* **27**: 473-519.
- Murray J. 1972.** *Genetic Diversity and Natural Selection*. Edinburgh: Oliver & Boyd.
- Orr HA. 2009.** Testing natural selection. *Scientific American* 44-51.
- Owen R. 1859.** *On the classification and geographical distribution of the mammalia, being the lecture on Sir Robert Reade's foundation, delivered before the University of Cambridge, in the Senate-House, May 10, 1859. To which is added an appendix "on the gorilla," and "on the extinction and transmutation of species"*. London: John Parker and son.
- Peccoud J, Ollivier A, Plantagenest M, Simon J-C. 2009.** Adaptive radiation in the pea aphid complex through gradual cessation of gene flow. *Proceedings of the National Academy of Sciences, USA* **106**: 7495-7500.
- Petersen W. 1903.** Entstehung der Arten durch physiologische Isolierung. *Biologisches Zentralblatt* **23**: 468-477.

- Pinzón JH, LaJeunesse TC. 2011.** Species delimitation of common reef corals in the genus *Pocillopora* using nucleotide sequence phylogenies, population genetics and symbiosis ecology. *Molecular Ecology* **xxx**: 000.
- Poulton EB. 1904.** What is a species? *Proceedings of the Entomological Society of London* **1903**: lxxvii-cxvi.
- Pritchard JK, Stephens M, Donnelly P. 2000.** Inference of population structure using multilocus genotype data. *Genetics* **155**: 945-959.
- Romanes GJ. 1886.** Physiological selection; an additional suggestion on the origin of species. *Journal of the Linnean Society of London (Zoology)* **19**: 337-411.
- Ruse M. 1980.** Charles Darwin and group selection. *Annals of Science* **37**: 615-630.
- Ruse M. 1987.** Biological species: natural kinds, individuals, or what? *British Journal for the Philosophy of Science* **38**: 225-242.
- Sloan PR. 2009.** Originating species. Darwin on the Species Problem. In: Richards RJ, Ruse M, eds. *The Cambridge Companion to the Origin of Species*. Cambridge: Cambridge University Press, 67-86.
- Stamos DN. 2006.** *Darwin and the Nature of Species*. Albany, NY: State University of New York Press.
- Wagner M. 1868.** *Darwin'sche Theorie und das Migrationsgesetz der Organismen*. Leipzig: Duncker & Humblot.
- Wagner M. 1873.** *The Darwinian Theory and the Law of the Migration of Organisms*, Translation by J.L. Laird of a paper published in 1868 ed. London: Edward Stanford.
- Wallace AR. 1886.** Physiological selection and the origin of species. *Nature (London)* **34**: 467-468.
- Wallace AR. 1889.** *Darwinism. An Exposition of the Theory of Natural Selection with Some of its Applications*. London: Macmillan & Co.
- Weisrock DW, Rasoloarison RM, Fiorentino I, Ralison JM, Goodman SM, Kappeler PM, Yoder AD. 2010.** Delimiting species without nuclear monophyly in Madagascar's mouse lemurs. *PLoS One* **5**: e9883.
- Wilson DS, Wilson EO. 2007.** Rethinking the theoretical foundation of sociobiology. *Quarterly Review of Biology* **82**: 327-348.
- Yang Z, Rannala B. 2010.** Bayesian species delimitation using multilocus sequence data. *Proceedings of the National Academy of Sciences, USA* **107**: 9264-9269.
- Zeng Y-F, Liao W-J, Petit RJ, Zhang D-Y. 2010.** Exploring species limits in two closely related Chinese oaks. *PLoS One* **5**: e15529.