such mutations are neutral as far as natural selection is concerned, being neither beneficial nor harmful, and can drift to fixation (that is, become an enduring part of the genome). The gradual accumulation of neutral mutations could erode previously adaptive structures and indirectly lead to habitat specialization. Alternatively, natural selection may actively re-sculpt the organism, reallocating resources from eyes which are useless in the dark to more useful structures (a pattern of correlated effects that geneticists call 'antagonistic pleiotropy' and ecologists call 'trade-offs'). But it is difficult to tell the difference between these causes of specialization in most natural populations[6]. This is why Cooper and Lenski have explored the problem not in a cave, but in a laboratory study of microbial evolution.

The short generation time and high abundance of microbes, and the experimental control possible in lab conditions, make microbes good subjects for evolutionary study. Lenski and colleagues[7] have been carrying out a long-term analysis of evolution in cultures of the bacterium *Escherichia coli*, and their system provides an ideal forum for investigating the genetic basis for a loss of ecological function — in this case, a decline in the ability of bacteria to use a variety of carbon sources for nutrition.

In their study[1], Cooper and Lenski confined replicate, genetically homogeneous lineages of bacteria to a simple environment (a minimal nutrient with glucose added). The lineages originated from an ancestral population sustained in a rich nutritive medium, with a smorgasbord of carbon substrates. Over 20,000 generations (taking about ten years in time), mutation resulted in increased adaptation of bacteria to glucose, with an accompanying decay in their ability to use alternative foodstuffs. In effect, *E. coli* growing on just glucose evolved to use a narrower diet, specializing to the available resource at the expense of their potential ability to live on alternative resources. This is comparable to cave fish which have lost a functional ability (sight) that is potentially useful in surface habitats.

Cooper and Lenski use several strands of evidence to argue that antagonistic pleiotropy has occurred. Mutations arise at random. So if functional loss occurs because of an accumulation of neutral mutations, one would expect an exponential decay in diet breadth. Instead, the decay was initially rapid but then slowed (mirroring the temporal dynamics of improved adaptation to glucose). Second, the pattern of functional loss was similar between the replicates. Because mutations arise independently in separate lineages, under the mutation-accumulation theory different functions should be knocked out first in different lineages. By and large, this did not happen.

Third, for one alternative resource (ribose), the molecular mechanism coupling the improved use of glucose to the reduced use of the alternative is understood: a separate study showed that the mutations that lead to a loss of capacity on ribose provide a selective advantage on glucose. Finally, if the mere accumulation of mutations leads to reduced ability to use a varied diet, higher mutation rates should result in higher rates of loss of that ability. Fortuitously, three lineages evolved changes that impaired their capacity for repairing damaged DNA, and so had much higher genome-wide mutation rates. But this elevated mutation rate had no significant effect on the rate of change in diet use.

Another, similar study[8] has also examined evolution in a microbial population with high mutation rates, but with an experimental regime leading to severe 'bottlenecks'. This is the situation when a population is reduced to very few members, which enhances random processes of genetic evolution at the expense of selection, and in particular facilitates the fixation of deleterious mutations. In this study[8], reduction in bacterial diet breadth was exponential in time, and unpredictable in pattern between replicate lineages — the patterns expected according to the mutation-accumulation theory. The contrast between this result and that of Cooper and Lenski[1] (where populations were large, greatly reducing the impact of random changes in genetic composition) also bolsters the case for trade-offs (antagonistic pleiotropy) being involved in ecological specialization in the latter experiment.

Nonetheless, many questions remain unanswered, both about Cooper and Lenski's experiments and their broader implications. A more quantitative characterization of the ancestral environment of the bacteria would be desirable, as would a mechanistic understanding of the metabolic constraints underlying antagonistic pleiotropy. Because Lenski's project is ongoing, further adaptive decay in diet breadth might emerge that is consistent with the mutation-accumulation hypothesis[9]. It would also be intriguing to examine evolutionary reversals. Can a lineage specialize to feed on a single nutrient and then re-evolve to use a generalized diet? If so, does this reversal become less likely, the longer the period of specialization? From comparative studies it seems that transitions from generalist to specialist occur more readily than in the other direction[10]. The lab system allows experimental assessment of such evolutionary asymmetries.

Microbes potentially provide solutions to environmental problems ranging from biological control of agricultural pests to cleaning up oil spills. So there are good practical reasons to understand the evolutionary constancy of microbial niches in natural environments, so as to assess the reliability and risks of such solutions. Generalizations to natural populations should of course be made with caution, given the simplified conditions of lab cultures. The bacterial strains in Lenski and Cooper's cultures are strictly asexual, whereas most natural populations can sexually exchange genetic material. This matters if the availability of genetic variation is a rate-limiting factor in evolution. Sexuality could also alter the expression of antagonistic pleiotropy and the rate of evolution towards ecological specialization.

Moreover, evolution in this study was driven only by selection on the ability to live on abiotic resources in lab environments that are relatively homogeneous in space and time, and occupied by a single bacterial species. In natural communities, specialization occurs in heterogeneous arenas[11] seething with other species, including competitors, predators and parasites. Also, the functional degradations assessed by Lenski and Cooper reflect changes in relative ability to use resources, not absolute losses of functions. So these results may better predict the exclusion of a particular lineage through indirect competition for resources (where exclusion may emerge from slight differences in two strains' relative abilities to use resources), than population persistence in competitor-free habitats (where exclusion may require the nearly complete absence of function).

Despite these caveats, the study by Cooper and Lenski provides valuable insights into the evolutionary dynamics of ecological specialization. These dynamics are central to the evolution of species diversity[12], and understanding them may even shed light on evolution in the stygian depths occupied by blind cave organisms. ■

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Daedalus

David Jones

David Jones, author of the Daedalus column, is indisposed.