Olivia Judson, an evolutionary biologist, is the author of "Dr. Tatiana's Sex Advice to All Creation: The Definitive Guide to the Evolutionary Biology of Sex," which was made into a three-part television program. Ms. Judson has been a reporter for The Economist and has written for a number of other publications, including Nature, The Financial Times, The Atlantic and Natural History. She is a research fellow in biology at Imperial College London.

March 11, 2008, 11:17 pm (New York Times)

Stop the Mutants!

Olivia Judson

This week, I'm going to do an impossible experiment.

I'm going to wave a magic wand and reduce the mutation rate to zero, instantly, in all species, and forever. Then I'm going to watch to see how long it takes for evolution to stop.

I'll report back in several millennia.

As I've mentioned in previous columns, mutations — accidental changes to DNA — provide the raw material for evolution. They make the difference between fur that is black and fur that is golden; between pink petals and blue ones; between the ability to fly over the Himalayas, as bar-headed geese do, and being able to stay underwater long enough to drown prey, as crocodiles can. Mutations are the ultimate cause of all the genetic differences we see around us; the ultimate cause of the differences between a human and a banana, between a starfish and a toadstool.

Crocodile, without prey. (Walter Astrada/Associated Press)

Actually stopping mutations is a physical impossibility — hence the need for a magic wand. But if they were to stop, so would raw invention.

But evolution would not. Not for a long time.

Although we often think of evolution in grand terms — a lineage of fish turning into frogs, or monkeys becoming apes — the technical definition is more humdrum. It's simply a change in the frequencies of different versions of a gene in a population over time.

To see how this can work, imagine a population of mosquitoes. Suppose most of them are sensitive to insecticide, but a few harbor a version of a gene that confers resistance. If you suddenly start spraying insecticide, you'll kill many of the mosquitoes that are sensitive; those that are resistant will be much more likely to reproduce, and will tend to leave more offspring. In the next generation, the frequency of the gene for resistance will have increased, and the population will have evolved a little. (For this article, I'm ignoring the possibility of evolution through non-genetic means, such as culture, which though important for humans is irrelevant for most other organisms.)

In short, a supply of genetic variation is all that's necessary for evolution to continue. And in most populations, genetic variation is already abundant.

Just look at us. Genetic differences among humans include differences in the ability to taste different flavors, digest alcohol or milk, or resist malaria or HIV; they include differences in skin, hair and eye color; in predispositions for heart disease or breast cancer; in amount of chest hair, the ability to grow a beard, the tendency towards baldness; the list goes on and on.

Nor is it just humans and our entourage of cats, dogs, sheep and company, that have lots of versions of lots of genes. Wild organisms in a given population vary genetically, too. Oak trees a few feet apart differ in the size and shape of their acorns. Male guppies from the same stream come in different colors, and with enormously different patterns of spots. Fruit flies from the same species differ in the number of bristles on their bellies; stalk-eyed flies differ in the lengths of their eye stalks. Galápagos finches, famously, differ in the shapes of their beaks.

Indeed, one of the great surprises of the past decades has been how much genetic variation there is, for there's far more than anyone expected. Some of this variation (exactly how much is the subject of debate) is meaningless, or "neutral" — it has absolutely no effect. But the rest can play a role in how well organisms survive and reproduce. Moreover, the utility of a gene depends on circumstances. Insecticide resistance genes are useful when there's insecticide about, but not when there isn't: then, they can be detrimental. In areas where insecticide is not sprayed, mosquitoes without the resistance gene do better. For some reason, having the resistance gene makes you less likely to survive the winter.

Since there's so much pre-existing variation, getting rid of mutation wouldn't cause evolution to grind to a halt until all the meaningful genetic variation ran out, leaving everyone in a population with the same sets of genes.

How long would that take? It depends. Some lifestyles, and some forces of nature, act to reduce genetic variation; others act to promote it. Let me give a few examples. (I'm not aiming to be comprehensive — if I went through the full list, we'd be here for hours.)

Among the forces that can cause genetic variation to disappear, one of the most severe is a population crash. For instance, in the 19th century, beavers were hunted to extinction in

Sweden. The present Swedish beaver population of around 100,000 is descended from fewer than 50 animals that were brought in from Norway in the 1920s. The small number of founders restricted how much variation there was to begin with, so it's not surprising that today's Swedish beavers show remarkably little genetic variation.

Natural selection can also, sometimes, be an agent of genetic uniformity. If natural selection consistently favors the same trait — such as insecticide resistance — then genes for insecticide resistance will sweep through the local population until everybody has them. Variation can then run out quite quickly: experiments where humans subject organisms to consistent and strong selection for a particular trait start to depend on new mutations after about 20 generations.

But the "if" is a big one. Natural selection may just gust about, favoring different sets of genes from one year to the next. As long as none of the gusts is too strong, lots of different genes can persist. Such gusting accounts for fluctuations in the beak shapes and body sizes of the Galápagos finches. Between 1972 and 2001, the beaks and bodies of two finch species on the island of Daphne Major were measured, and shown to wander, beaks shifting about from blunt to pointy, bodies, from large to small. Natural selection blew in the same direction — i.e., favored the same sets of characteristics — for, at most, three years in a row.

And sometimes natural selection actively promotes the persistence of genetic variation. This can happen when there's an advantage to having genes that are rare. Among guppies, for example, males with rare color patterns are much more likely to survive than those with common color patterns, presumably because predators get good at spotting the patterns they encounter often. In such situations, the rare type does well, begins to become common — and then becomes the victim of its own success and starts to do badly. In situations like this, the frequencies of different genes can rise and fall, cycling indefinitely.

Among lifestyles that promote genetic diversity, far and away the most important is sex. Sex shuffles up genes, continually producing new gene combinations. (An important difference between sex and mutation is that sex can only create genetic novelty if it already exists in the population. If everyone is genetically identical, sex will have no effect.) Sex also — and this is important — decouples the fates of genes from one another. For example, sex means that genes involved in fur color and genes involved in, say, blood type, can be inherited independently — you get a mix of the genes your parents had. Asexuals, on the other hand, are genetically identical to their parent — they are clones. If one of their genes becomes strongly detrimental, the whole genome can be lost.

But sex isn't the only diversity-boosting lifestyle. For many plants, genetic diversity isn't limited to what you see in genomes here and now. Large numbers of genetic time capsules — i.e., seeds — remain buried in the soil, a phenomenon known as a seed bank. And although the seeds of some plants don't remain viable for long, the seeds of others can germinate after sitting in the soil for decades or (occasionally) centuries. A seed from a sacred lotus fruit that had been buried in a dry lake bed for around 1,000 years sprouted when it was dug up, planted and watered.

(In the case of the lotus, the age was worked out by carbon dating of the fruit. In general,

however, it's hard to know for sure how old an old seed is. But thanks to the foresight of a certain Dr. William James Beal, a seed viability experiment has been going on in East Lansing, Michigan, for more than 120 years. In 1879, Dr. Beal buried 20 bottles each containing sandy soil and a mixture of seeds from 21 different species. At regular intervals, a bottle is dug up, and the sand-seed mix is transferred into a shallow tray of soil and watered. Most recently — the 120th year — 26 seeds from three different species sprouted, and several of the plants went on to produce normal seeds in turn. The next bottle is due to be dug up in 2020.)

Since seed banks can contain as much, or more, genetic variation as living plants, they can buffer plant populations against the loss of genes: a gene that vanishes today may be reinstated at some stage in the future. A few animals also have a capacity for time travel. Tardigrades and rotifers — small invertebrates — are among those that have evolved the ability to go into suspended animation in tough times. Rejuvenation can take place a few years later: here again, genes that were lost can reappear.

What all this means is that even if I waved my wand and stopped mutation for good, there are at least some species in which evolution could carry on for ages, perhaps indefinitely.

I'll let you know in a million years.

****

NOTES:

For the mutations that allow the bar-headed goose to fly so high, see Liang, Y. H., Liu, X. Z., Liu, S. H., and Lu, G. Y. 2001. "The structure of greylag goose oxy-haemoglobin: the roles of four mutations compared with bar-headed goose haemoglobin." Acta Crystallographica D: Biological Crystallography 57: 1850-1856. For the mutations that allow crocodiles to stay submerged while drowning prey, see Komiyama, N. H., Miyazaki, G., Tame, J., and Nagai, K. 1995. "Transplanting a unique allosteric effect from crocodile into human haemoglobin." Nature 373: 244-246.

For the importance of pre-existing genetic variation in the evolution of natural populations, see Barrett, R. D. H., and Schluter, D. 2008. "Adaptation from standing genetic variation." Trends in Ecology and Evolution 23: 38-44. Examples of genetic variation in humans and in natural populations can be found in any textbook on evolution or population genetics. For variation running out in artificial selection, and for a general review of the forces that maintain genetic diversity, see Barton, N. H., and Keightley, P. D. 2002. "Understanding quantitative genetic variation." Nature Reviews Genetics 3: 11-21.

For insecticide resistance genes and their costs in mosquitoes, see Lenormand, T., Bourguet, D., Guillemaud, T., and Raymond, M. 1999. "Tracking the evolution of insecticide resistance in the mosquito Culex pipiens." Nature 400: 861-864.

For low genetic variation in Swedish beavers, and a history of the population, see Ellegren,

H., Hartman, G., Johansson, M., and Andersson, L. 1993. "Major histocompatibility complex monomorphism and low levels of DNA fingerprinting variability in a reintroduced and rapidly expanding population of beavers." Proceedings of the National Academy of Sciences 90: 8150-8153.

For gusty natural selection in the Galápagos finches, see Grant, P. R., and Grant, B. R. 2002. "Unpredictable evolution in a 30-year study of Darwin's finches." Science 296: 707-711. For the advantage of being rare in guppies, see Olendorf, R. et al 2006. "Frequency-dependent survival in natural guppy populations." Nature 441: 633-636.

For germination of the sacred lotus, and the age of the seeds, see Shen-Miller, J., Mudgett, M. B., Schopf, J. W., Clarke, S., and Berger, R. 1995. "Exceptional seed longevity and robust growth: ancient sacred lotus from China." American Journal of Botany 82: 1367-1380. For Dr. Beal's long-term seed experiment, see Telewski, F. W., and Zeevaart, J. A. D. 2002. "The 120-year period for Dr. Beal's seed viability experiment." American Journal of Botany 89: 1285-1288. For genetic variability in seed banks compared with living plants, see, for example Uchiyama, K., Goto, S., Tsuda, Y., Takahashi, Y., and Ide, Y. 2006. "Genetic diversity and genetic structure of adult and buried seed populations of Betula maximowicziana in mixed and post-fire stands." Forest Ecology and Management 237: 119-126.

For rejuvenation of rotifers and tardigrades after lengthy periods of anhydrobiosis, see Guidetti, R., and Jönsson, K. I. 2002. "Long-term anhydrobiotic survival in semi-terrestrial micrometazoans." Journal of Zoology 257: 181-187.