LETTER

Reply to Lane and Martin: Being and becoming eukaryotes

In their letter, Lane and Martin (1) take us to task for our treatment (2) of their earlier paper (3). In that paper (3), there is much about genes, albeit mostly about the cost of their expression, not their replication. The focus is on how many additional genes mitochondria allow cells to have, and the number of different proteins they might thus make. For example, Lane and Martin write (3), "The endosymbiosis that gave rise to mitochondria restructured the distribution of DNA in relation to bioenergetic membranes, permitting a remarkable 200,000-fold expansion in the number of genes expressed," and again that, "Mitochondria increased the number of proteins that a cell can evolve, inherit and express by four to six orders of magnitude . . .," noting that "The implications for complexity can hardly be overstated."

Perhaps, but there are prokaryotes with half as many genes as us and eukaryotes with fewer genes than *Escherichia coli*. An enormous expansion in gene number was not necessary and hasn't happened! Eukaryotes do have larger cells than prokaryotes on average, thus needing more proteins and more energy to make them. But they seem not to need hugely many more different proteins. It may be that energy is limiting in the evolution of big, active eukaryotes like us, but the limitation is not primarily on "the number of proteins that a cell can evolve" (3).

We acknowledge Lane and Martin's (1) second point, as their paper (3) did give reasons for prokaryotes failing to evolve eukaryote-like morphological complexity, principally that prokaryotes would need "giant plasmids encoding components of the electron transport chain," which are unlikely to be carried in high copy number. But our own mitochondrial genomes boast scarcely a dozen genes encoding components of the electron transport chain. Moreover, some eukaryotes have "mitochondria-related organelles" with no such genes. So cells don't need compartmentalized genomes dedicated to respiration to be eukaryotes.

Which brings us to Lane and Martin's (1) third argument, that cells nevertheless need such compartmentalized genomes and the extra energy they provide to become eukaryotes. Lane and Martin offer the analogy that "it takes far more energy to build a suspension bridge than it does to maintain it, once finished" (1). But cells aren't bridges. They are constantly taking themselves apart and rebuilding themselves, and of course such maintenance takes metabolic energy. We agree that the sudden gratuitous acquisition of excess energy (bestowed by the mitochondrial symbiosis) could be permissive of complexification. But Darwinian evolution itself is not energy-driven. The cost of successive fixations of beneficial mutations is borne by populations (as selective deaths), not by cells as a metabolic cost. That there are eukaryotes with the usual cellular features but no energy-producing mitochondria testifies that such things could evolve. Thus, we [like Szathmáry (4)] remain unconvinced that the evolution of eukaryotic cellular complexity required the input of extra energy. And we question that the evolution of eukaryotic organismal complexity (multicellularity) required anything like the "remarkable 200,000-fold expansion in the number of genes expressed" that Lane and Martin (3) tout as the signal benefit of mitochondrial acquisition.

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1 Lane N, Martin WF (2015) Eukaryotes really are special, and mitochondria are why. *Proc Natl Acad Sci USA* 112:E4823.

2 Booth A, Doolittle WF (2015) Eukaryogenesis, how special really? *Proc Natl Acad Sci USA* 112(33):10278–10285.

3 Lane N, Martin W (2010) The energetics of genome complexity. *Nature* 467(7318):929–934.

4 Szathmáry E (2015) Toward major evolutionary transitions theory 2.0. *Proc Natl Acad Sci USA* 112(33):10104–10111.

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