ENDNOTES

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Does the Anthropic Principle Include Biochemistry?

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Introduction

1. Daniel J. Levitin, *This Is Your Brain on Music: The Science of a Human Obsession* (New York: Dutton, 2006).
2. *Encyclopedia of Human Evolution and Prehistory*, ed. Eric Delson et al., 2nd ed. (New York: Garland, 2000), s.vv. "Late Paleolithic," "Later Stone Age."
3. Christopher S. Henshilwood et al., "An Abstract Drawing from the 73,000-Year-Old Levels at Blombos Cave, South Africa," *Nature* 562 (October 4, 2018): 115–18, doi:10.1038/s41586-018-0514-3.
4. Levitin, *Your Brain on Music*, 6.
5. For example, see Iris Berent et al., "Language Universals in Human Brains," *Proceedings of the National Academy of Sciences, USA* 105, no. 14 (April 8, 2008): 5321–25, doi:10.1073/pnas.0801469105; Iris Berent et al., "Language Universals Engage Broca's Area," *PLOS ONE* 9, no. 4 (April 17, 2014): e95155, doi:10.1371/journal.pone.0095155.
6. Catherine Matacic, "Rhythm Might Be Hardwired in Humans," *Science* (December 19, 2016): doi:10.1126/science.aal0531.
7. Virginia Hughes, "Why Does Music Feel So Good?" *National Geographic*, April 11, 2013, nationalgeographic.com/science/article/why-does-music-feel-so-good.
8. Diane Koopman, "The Science Behind Why Music Makes Us Feel So Good," *Lifehack*, lifehack.org/361240/the-science-behind-why-music-makes-feel-good.
9. Christopher Bergland, "Why Do the Songs from Your Past Evoke Such Vivid Memories?" *Psychology Today*, December 11, 2013, psychologytoday.com/us/blog/the-athletes-way/201312/why-do-the-songs-your-past-evoke-such-vivid-memories.
10. Bergland, "Songs from Your Past?"
11. Taylor Pittman, "Why You Like Listening to the Same Song Over and Over Again," *HuffPost Canada*, May 24, 2018, huffingtonpost.ca/entry/why-you-like-listening-same-song_n_5b06c900e4b05f0fc8458fc2.
12. Pittman, "Listening to the Same Song."
13. Brandon Carter, "Large Number Coincidences and the Anthropic Principle in Cosmology," *International Astronomical Union Symposium* 63 (1974): 291–98, doi:10.1017/s0074180900235638.
14. Michael J. Denton, *Nature's Destiny: How the Laws of Biology Reveal Purpose in the Universe* (New York: Free Press, 1998).
15. John D. Barrow et al., ed., *Fitness of the Cosmos for Life: Biochemistry and Fine-Tuning* (New York: Cambridge University Press, 2008).

Chapter 1: The Cosmological Anthropic Principle

1. David Browne, "Baby Hold On: Why Eddie Money Was the Patron Saint of Rock Uncool," *Rolling Stone*, September 13, 2019, rollingstone.com/music/music-features/eddie-money-appreciation-884179/.
2. Browne, "Baby Hold On."
3. A great summary of the history of the anthropic principle can be found in the chapter written by Ernan McMullin called "Tuning Fine-Tuning" for the treatise from John D. Barrow et al., ed., *Fitness of the Cosmos for Life: Biochemistry and Fine Tuning* (New York: Cambridge University Press, 2008), 70–94.
4. An accessible discussion on the effect of altering the universe's dimensions can be found in Geraint F. Lewis and Luke A. Barnes, *A Fortunate Universe: Life in a Finely Tuned Cosmos* (Cambridge: Cambridge University Press, 2016), 221–26.
5. An accessible discussion on the effect of altering the universe's expansion rate can be found in Lewis and Barnes, *A Fortunate Universe,* 221–26, and in Hugh Ross's *The Creator and the Cosmos: How the Latest Scientific Discoveries Reveal God*, 4th ed. (Covina, CA: RTB Press, 2018), 45–57, 237.
6. An excellent discussion of dark energy can be found in Ross's *Creator and the Cosmos,* 45–57.
7. Ross, *Creator and the Cosmos,* 233.
8. Ross, *Creator and the Cosmos*, 233–41.

Chapter 2: The Father of the Anthropic Principle

1. "500 Greatest Songs of All Time," *Rolling Stone*, December 11, 2003, rollingstone.com/music/music-lists/500-greatest-songs-of-all-time-151127/.
2. The material for this section is taken from an essay by Everett Mendelsohn, "Locating 'Fitness' and L. J. Henderson," in John D. Barrow et al., ed., *Fitness of the Cosmos for Life: Biochemistry and Fine Tuning* (New York: Cambridge University Press, 2008), 3–19.
3. Lawrence J. Henderson, *The Fitness of the Environment: An Inquiry into the Biological Significance of the Properties of Matter* (New York: Macmillan, 1913), vi–vii.
4. Henderson, *Fitness of the Environment*, 272.
5. Henderson, *Fitness of the Environment*, viii.
6. Henderson, *Fitness of the Environment*, 269.
7. Henderson, *Fitness of the Environment*, 271.
8. Henderson, *Fitness of the Environment*, 275.
9. Henderson, *Fitness of the Environment*, 279.
10. Henderson, *Fitness of the Environment*, 281.
11. Henderson, *Fitness of the Environment*, 308.
12. Lawrence J. Henderson, *The Order of Nature: An Essay* (Cambridge, MA: Harvard University Press, 1917), 8–9.
13. Henderson, *Order of Nature*, 191–92.

14. Henderson, *Order of Nature*, 201.
15. Mendelsohn, "Locating 'Fitness,'" 3–19.
16. John D. Barrow, "Chemistry and Sensitivity," in Barrow et al., *Fitness of the Cosmos*, 135.
17. Mendelsohn, "Locating 'Fitness,'" 3–19.

Chapter 3: The Chemical Anthropic Principle

1. Owen Gingerich, "Revisiting the Fitness of the Environment," in Barrow et al., *Fitness of the Cosmos*, 23.
2. Simon Conway Morris and Ard A. Louis, "Is Water an Amniotic Eden or a Corrosive Hell? Emerging Perspectives on the Strangest Fluid in the Universe," in *Water and Life: The Unique Properties of* H_2O, ed. Ruth M. Lynden-Bell et al. (Boca Raton, FL: CRC Press, 2010), 3.
3. For example, see Michael J. Denton, *Nature's Destiny: How the Laws of Biology Reveal Purpose in the Universe* (New York: Free Press, 1998), 19–46. Also, Reasons to Believe hosts a seven-part series of articles written by chemists Dr. John Millam, Iain D. Sommerville, and environmental scientist Ken Klos, entitled "Water: Designed for Life," reasons.org/explore/blogs/todays-new-reason-to-believe/read/tnrtb/2013/05/20/water-designed-for-life-part-1-(of-7).
4. Charles Tanford, *The Hydrophobic Effect: Formation of Micelles and Biological Membranes* (New York: John Wiley & Sons, 1973); Charles Tanford, "The Hydrophobic Effect and the Organization of Living Matter," *Science* 200, no. 4345 (June 2, 1978): 1012–18, doi:10.1126/science.653353.
5. Martin F. Chaplin, "Water's Hydrogen Bond Strength," in Lynden-Bell et al., *Water and Life*, 69–86.
6. Morris and Louis, "Water an Amniotic Eden?," 8–9.
7. For a more comprehensive discussion of the beneficial properties of carbon dioxides that exert their influence on a planetary scale, see Denton, *Nature's Destiny*, 90–92.
8. Henderson, *Fitness of the Environment*, 135–36.
9. Ali Naqui, Britton Chance, and Enrique Cadenas, "Reactive Oxygen Intermediates in Biochemistry," *Annual Reviews of Biochemistry* 55 (1986): 137–66, doi:10.1146/annurev.bi.55.070186.001033.

Chapter 4: Proteins

1. For a discussion of the complexity of the simplest cell, see my book *The Cell's Design: How Chemistry Reveals the Creator's Artistry* (Grand Rapids, MI: Baker Books, 2008), 53–67.
2. Michael J. Denton, "Protein-Based Life as an Emergent Property of Matter: The Nature and Biological Fitness of Protein Folds," in John D. Barrow et al., ed., *Fitness of the Cosmos for Life: Biochemistry and Fine Tuning* (New York: Cambridge University Press, 2008), 260.
3. Stephen Jay Gould, *Wonderful Life: The Burgess Shale and the Nature of History* (New York: W. W. Norton, 1990).
4. For example, see Toshiki Koga and Hiroshi Naraoka, "A New Family of Extraterrestrial Amino Acids in the Murchison Meteorite," *Science Reports* 7 (April 4, 2017): 636, doi.org/10.1038/s41598-017-00693-9.
5. Arthur L. Weber and Stanley L. Miller, "Reasons for the Occurrence of the Twenty Coded Protein Amino Acids," *Journal of Molecular Evolution* 17, no. 5 (September 1981): 273–84, doi:10.1007/bf01795749; H. James Cleaves II, "The Origin of the Biologically Coded Amino Acids," *Journal of Theoretical Biology* 263, no. 4 (April 21, 2010): 490–98, doi:10.1016/j.jtbi.2009.12.014.
6. Gayle K. Philip and Stephen J. Freeland, "Did Evolution Select a Nonrandom 'Alphabet' of Amino Acids?," *Astrobiology* 11, no. 3 (April 2011): 235–40, doi:10.1089/ast.2010.0567.
7. Philip and Freeland, "Nonrandom 'Alphabet' of Amino Acids?," 235–40.
8. Melissa Ilardo et al., "Adaptive Properties of the Genetically Encoded Amino Acid Alphabet Are Inherited from Its Subsets," *Scientific Reports* 9 (August 28, 2019): 12468, doi:10.1038/s41598-019-47574-x.
9. Matthias Granold et al., "Modern Diversification of the Amino Acid Repertoire Driven by Oxygen," *Proceedings of the National Academy of Sciences, USA* 115, no. 1 (January 2, 2018): 41–46, doi:10.1073/pnas.1717100115.
10. Jayanth R. Banavar and Amos Maritan, "Life on Earth: The Role of Proteins," in Barrow et al., *Fitness of the Cosmos*, 249.
11. Christine A. Orengo and Janet M. Thornton, "Protein Families and Their Evolution—A Structural Perspective," *Annual Review of Biochemistry* 74 (July 7, 2005): 867–900, doi:10.1146/annurev.biochem.74.082803.133029.
12. Denton, "Protein-Based Life," in Barrow et al., *Fitness of the Cosmos*, 256–79.
13. Cyrus Chothia et al., "Protein Folds in the All-β and All- αClasses," *Annual Review of Biophysics and Biomolecular Structure* 26 (June 1997): 597–627, doi:10.1146/annurev.biophys.26.1.597.
14. Chothia et al., "Protein Folds," 597–627.
15. Lijia Yu et al., "Grammar of Protein Domain Architectures," *Proceedings of the National Academy of Sciences, USA* 116, no. 9 (February 26, 2019): 3636–45, doi:10.1073/pnas.1814684116.
16. It should be noted that not all proteins automatically fold into the correct three-dimensional shape after they are produced at the ribosome. Even though physicochemical constraints exist, proteins can often misfold. Correct folding requires the assistance of chaperone proteins.
17. Banavar and Maritan, "Life on Earth," 225–55.
18. Banavar and Maritan, "Life on Earth," 239, 250.
19. Sven Hovmöller, Tuping Zhou, and Tomas Ohlson, "Conformations of Amino Acids in Proteins," *Acta Crystallographica D* 58, no. 5 (May 2002): 768–76, doi:10.1107/s0907444902003359.
20. Peter Y. Chou and Gerald D. Fasman, "Conformational Parameters for Amino Acids in Helical, β-Sheet, and Random Coil

Regions Calculated from Proteins," *Biochemistry* 13, no. 2 (January 15, 1974): 211–22, doi.org/10.1021/bi00699a001.
21. Hang Chen, Fei Gu, and Zhengge Huang, "Improved Chou-Fasman Method for Protein Secondary Structure Prediction," *BMC Bioinformatics* 7 (December 12, 2006): S14, doi:10.1186/1471-2105-7-S4-S14.
22. Jeffrey Skolnick and Mu Gao, "Interplay of Physics and Evolution in the Likely Origin of Protein Biochemical Function," *Proceedings of the National Academy of Sciences, USA* 110, no. 23 (June 4, 2013): 9344–49, doi:10.1073/pnas.1300011110.
23. Mu Gao and Jeffrey Skolnick, "A Comprehensive Survey of Small-Molecule Binding Pockets in Proteins," *PLOS Computational Biology* 10 (October 24, 2013): e1003302, doi:10.1371/journal.pcbi.1003302.
24. Skolnick and Gao, "Interplay of Physics," 9344–49.
25. Banavar and Maritan, "Life on Earth," 250.
26. European Molecular Biology Laboratory–European Bioinformatics Institute, "Periodic Table of Protein Complexes," *ScienceDaily*, December 10, 2015, sciencedaily.com/releases/2015/12/151210144539.htm.
27. Sebastian E. Ahnert et al., "Principles of Assembly Reveal a Periodic Table of Protein Complexes," *Science* 350, no. 6266 (December 11, 2015): doi:10.1126/science.aaa2245.
28. Elke Deuerling and Bernd Bukau, "Chaperone-Assisted Folding of Newly Synthesized Proteins in the Cytosol," *Critical Reviews in Biochemistry and Molecular Biology* 39, no. 5 (2004): 261–77, doi:10.1080/10409230490892496.
29. Yun-Chi Tang et al., "Structural Features of the GroEL-GroES Nano-Cage Required for Rapid Folding of Encapsulated Protein," *Cell* 125, no. 5 (June 2, 2006): 903–14, doi:10.1016/j.cell.2006.04.027.

Chapter 5: The Nucleic Acids

1. Francis S. Collins recounts this story in his book *The Language of God: A Scientist Presents Evidence for Belief* (New York: Free Press, 2006), 2–3.
2. Collins, *Language of God*, 3.
3. Georgi Muskhelishvili and Andrew Travers, "Integration of Syntactic and Semantic Properties of the DNA Code Reveals Chromosomes as Thermodynamic Machines Converting Energy into Information," *Cellular and Molecular Life Sciences* 70, no. 23 (December 2013): 4555–67, doi.10.1007/s00018-013-1394-1.
4. F. H. Westheimer, "Why Nature Chose Phosphates," *Science* 235, no. 4793 (March 6, 1987): 1173–78, doi:10.1126/science.2434996.
5. Felisa Wolfe-Simon et al., "A Bacterium That Can Grow by Using Arsenic Instead of Phosphorus," *Science* 332, no. 6034 (June 3, 2011): 1163–66, doi:10.1126/science.1197258.
6. Dan S. Tawfik and Ronald E. Viola, "Arsenate Replacing Phosphate—Alternative Life Chemistries and Ion Promiscuity," *Biochemistry* 50, no. 7 (February 22, 2011): 1128–34, doi: 10.1021/bi200002a.
7. Yu Xu et al., "Structural and Functional Consequences of Phosphate-Arsenate Substitutions in Selected Nucleotides: DNA, RNA, and ATP," *Journal of Physical Chemistry B* 116, no. 16 (April 26, 2012): 4801–11, doi:10.1021/jp300307u.
8. Ryszard Kierzek, Liyan He, and Douglas H. Turner, "Association of 2′–5′ Oligoribonucleotides," *Nucleic Acids Research* 20, no. 7 (April 11, 1992): 1685–90, doi:10.1093/nar/20.7.1685.
9. Gaspar Banfalvi, "Why Ribose Was Selected as the Sugar Component of Nucleic Acids," *DNA and Cell Biology* 25, no. 3 (March 2006): 189–96, doi:10.1089/dna.2006.25.189.
10. Huiqing Zhou et al., "m^1A and m^1G Disrupt A-RNA Structure through the Intrinsic Instability of Hoogsteen Base Pairs," *Nature Structural and Molecular Biology* 23 (September 2016): 803–10, doi:10.1038/nsmb.3270.
11. For example, see Albert Eschenmoser, "Chemical Etiology of Nucleic Acid Structure," *Science* 284, no. 5423 (June 25, 1999): 2118–24, doi:10.1126/science.284.5423.2118.
12. As a case in point, see Eveline Lescrinier, Matheus Froeyen, and Piet Herdewijn, "Difference in Conformational Diversity between Nucleic Acids with a Six-Membered 'Sugar' Unit and Natural 'Furanose' Nucleic Acids," *Nucleic Acids Research* 31, no. 12 (June 15, 2003): 2975–89, doi:10.1093/nar/gkg407.
13. Stanley L. Miller, "The Endogenous Synthesis of Organic Compounds," in *The Molecular Origins of Life: Assembling Pieces of the Puzzle*, ed. Andri Brack (Cambridge: Cambridge University Press, 1998), 59–85, doi:10.1017/cbo9780511626180.005.
14. Jean-Marc L. Pecourt, Jorge Peon, and Bern Kohler, "Ultrafast Internal Conversion of Electronically Excited RNA and DNA Nucleosides in Water," *Journal of the American Chemical Society* 122, no. 38 (September 1, 2000): 9348–49, doi:10.1021/ja0021520.
15. Dónall A. Mac Dónaill, "A Parity Code Interpretation of Nucleotide Alphabet Composition," Chemical Communications 18 (September 21, 2002): 2062–63; Dónall A. Mac Dónaill, "Why Nature Chose A, C, G and U/T: An Error-Coding Perspective of Nucleotide Alphabet Composition," *Origins of Life and Evolution of the Biosphere* 33 (October 2003): 433–55, doi:10.1023/a:1025715209867.
16. Reiner Veitia and Chris Ottolenghi, "Placing Parallel Stranded DNA in an Evolutionary Context," *Journal of Theoretical Biology* 206, no. 2 (September 21, 2000): 317–22, doi:10.1006/jtbi.2000.2119.
17. For example, see Stephanie A. Havemann et al., "Incorporation of Multiple Sequential Pseudothymidines by DNA Polymerases and Their Impact on DNA Duplex Structure," *Nucleosides, Nucleotides, and Nucleic Acids* 27, no. 3 (March 2008): 261–78, doi:10.1080/15257770701853679; Shuichi Hoshika et al., "Hachimoji DNA and RNA: A Genetic System with Eight Building Blocks," *Science* 363, no. 6429 (February 22, 2019): 884–87, doi:10.1126/science.aat0971.
18. H. James Cleaves II, Markus Meringer, and Jay Goodwin, "227 Views of RNA: Is RNA Unique in Its Chemical Isomer

Space?” *Astrobiology* 15, no. 7 (July 2015): 538–58, doi:10.1089/ast.2014.1213; H. James Cleaves II et al., “One among Millions: The Chemical Space of Nucleic Acid-Like Molecules,” *Journal of Chemical Information and Modeling* 59, no. 10 (October 28, 2019): 4266–77, doi:10.1021/acs.jcim.9b00632.
19. Tokyo Institute of Technology, “DNA Is Only One among Millions of Possible Genetic Molecules,” *ScienceDaily,* November 11, 2019, sciencedaily.com/releases/2019/11/191111084915.htm.
20. Simon Conway Morris, *Life’s Solution: Inevitable Humans in a Lonely Universe* (Cambridge: Cambridge University Press, 2003), 27–31.
21. Conway Morris, *Life’s Solution*, 27–31.
22. M. R. Arkin et al., “Rates of DNA-Mediated Electron Transfer between Metallointercalators,” *Science* 273, no. 5274 (July 26, 1996): 475–80, doi:10.1126/science.273.5274.475; Peter J. Dandliker, R. Erik Holmlin, and Jacqueline K. Barton, “Oxidative Thymine Dimer Repair in the DNA Helix,” *Science* 275, no. 5305 (March 7, 1997): 1465–68, doi:10.1126/science.275.5305.1465.
23. Amie K. Boal et al., “Redox Signaling between DNA Repair Proteins for Efficient Lesion Detection,” *Proceedings of the National Academy of Sciences, USA* 106, no. 36 (September 8, 2009): 15237–42, doi:10.1073/pnas.0908059106; Pamela A. Sontz et al., “DNA Charge Transport as a First Step in Coordinating the Detection of Lesions by Repair Proteins,” *Proceedings of the National Academy of Sciences, USA* 109, no. 6 (February 7, 2012): 1856–61, doi:10.1073/pnas.1120063109; Michael A. Grodick, Natalie B. Muren, and Jacqueline K. Barton, “DNA Charge Transport within the Cell,” *Biochemistry* 54, no. 4 (February 3, 2015): 962–73, doi:10.1021/bi501520w.
24. Elizabeth O’Brien et al., “The [4Fe4S] Cluster of Human DNA Primase Functions as a Redox Switch Using DNA Charge Transport,” *Science* 355, no. 6327 (February 24, 2017): eaag1789, doi:10.1126/science.aag1789.
25. Kamaludin Dingle, Steffan Schaper, and Ard A. Louis, “The Structure of the Genotype-Phenotype Map Strongly Constrains the Evolution of Non-Coding RNA,” *Interface Focus* 5, no. 6 (December 6, 2015): 20150053, doi:10.1098/rsfs.2015.0053.

Chapter 6: The Synthesis of Proteins and Nucleic Acids

1. Francis Crick, *What Mad Pursuit: A Personal View of Scientific Discovery* (New York: Basic Books, 1988), 109.
2. Ian S. Dunn, “Are Molecular Alphabets Universal Enabling Factors for the Evolution of Complex Life?” *Origins of Life and Evolution of Biospheres* 43, no. 6 (December 2013): 445–64, doi:10.1007/s11084-014-9354-9.
3. Francis Crick, “The Origin of the Genetic Code,” *Journal of Molecular Biology* 38, no. 3 (December 28, 1968): 367–79, doi:10.1016/0022-2836(68)90392-6.
4. Crick, “Origin of the Genetic Code,” 367–79.
5. Stephen J. Freeland, “Could an Intelligent Alien Predict Earth’s Biochemistry?,” in John D. Barrow et al., ed., *Fitness of the Cosmos for Life: Biochemistry and Fine-Tuning* (New York: Cambridge University Press, 2008), 300.
6. Hubert P. Yockey, *Information Theory and Molecular Biology* (Cambridge: Cambridge University Press, 1992), 180–83.
7. Malgorzata Wnętrzak et al., “The Optimality of the Standard Genetic Code Assessed by an Eight-Objective Evolutionary Algorithm,” *BMC Evolutionary Biology* 18, no. 1 (December 18, 2018): 192, doi:10.1186/s12862-018-1304-0.
8. David Haig and Laurence D. Hurst, “A Quantitative Measure of Error Minimization in the Genetic Code,” *Journal of Molecular Evolution* 33 (November 1991): 412–17, doi:10.1007/bf02103132.
9. Gretchen Vogel, “Tracking the History of the Genetic Code,” *Science* 281, no. 5375 (July 17, 1998): 329, doi:10.1126/science.281.5375.329; Stephen J. Freeland and Laurence D. Hurst, “The Genetic Code Is One in a Million,” *Journal of Molecular Evolution* 47, no. 3 (September 1998): 238–48, doi:10.1007/pl00006381; Stephen J. Freeland, Tao Wu, and Nick Keulmann, “The Case for an Error Minimizing Standard Genetic Code,” *Origins of Life and Evolution of the Biosphere* 33 (October 2003): 457–77, doi:10.1023/A:1025771327614; Stephen J. Freeland, Robin D. Knight, and Laura F. Landweber, “Measuring Adaptation within the Genetic Code,” *Trends in Biochemical Sciences* 25, no. 2 (February 1, 2000): 44–45, doi:10.1016/s0968-0004(99)01531-5; Stephen J. Freeland and Laurence D. Hurst, “Load Minimization of the Genetic Code: History Does Not Explain the Pattern,” *Proceedings of the Royal Society B Biological Sciences* 265, no. 1410 (November 7, 1998): 2111–19, doi:10.1098/rspb.1998.0547; J. Gregory Caporaso, Michael Yarus, and Rob Knight, “Error Minimization and Coding Triplet/Binding Site Associations Are Independent Features of the Canonical Genetic Code,” *Journal of Molecular Evolution* 61, no. 5 (November 2005): 597–607, doi:10.1007/s00239-004-0314-2.
10. Dimitri Gilis et al., “Optimality of the Genetic Code with Respect to Protein Stability and Amino-Acid Frequencies,” *Genome Biology* 2 (October 24, 2001): doi:10.1186/gb-2001-2-11-research0049.
11. Artem S. Novozhilov, Yuri I. Wolf, and Eugene V. Koonin, “Evolution of the Genetic Code: Partial Optimization of a Random Code for Robustness to Translation Error in a Rugged Fitness Landscape,” *Biology Direct* 2 (October 23, 2007): 24, doi:10.1186/1745-6150-2-24; Eugene V. Koonin and Artem S. Novozhilov, “Origin and Evolution of the Genetic Code: The Universal Enigma,” *IUBMB Life* 61, no. 2 (February 2009): 99–111, doi:10.1002/iub.146; Stephen J. Freeland et al., “Early Fixation of an Optimal Genetic Code,” *Molecular Biology and Evolution* 17, no. 4 (April 2000): 511–18, doi:10.1093/oxfordjournals.molbev.a026331; Wnętrzak et al., “Optimality of the Standard Genetic Code,” 192.
12. Freeland et al., “Early Fixation,” 511–18.
13. Regine Geyer and Amir Madany Mamlouk, “On the Efficiency of the Genetic Code after Frameshift Mutations,” *PeerJ* 6 (May 21, 2018): e4825, doi:10.7717/peerj.4825.
14. Stefan Wichmann and Zachery Ardern, “Optimality in the Standard Genetic Code Is Robust with Respect to Comparison Code Sets,” *Biosystems* 185 (November 2019): id. 104023, doi:10.1016/j.biosystems.2019.104023.
15. Wichmann and Ardern, “Optimality.”

16. Shalev Itzkovitz and Uri Alon, “The Genetic Code Is Nearly Optimal for Allowing Additional Information within Protein-Coding Sequences,” *Genome Research* 17, no. 4 (April 2007): 405–12, doi:10.1101/gr.5987307.
17. Liat Shenhav and David Zeevi, “Resource Conservation Manifests in the Genetic Code,” *Science* 370, no. 6517 (November 6, 2020): 683–87, doi:10.1126/science.aaz9642.
18. Wichmann and Ardern, “Optimality.”
19. Freeland et al., “Early Fixation,” 511–18.
20. Aline Bender, Parvana Hajieva, and Bernd Moosmann, “Adaptive Antioxidant Methionine Accumulation in Respiratory Chain Complexes Explains the Use of a Deviant Genetic Code in Mitochondria,” *Proceedings of the National Academy of Sciences, USA* 105, no. 43 (October 28, 2008): 16496–501, doi:10.1073/pnas.0802779105.
21. Shlomi Reuveni, Måns Ehrenberg, and Johan Paulsson, “Ribosomes Are Optimized for Autocatalytic Production,” *Nature* 547 (July 20, 2017): 293–97, doi:10.1038/nature22998.
22. Xinzhu Wei and Jianzhi Zhang, “On the Origin of Compositional Features of Ribosomes,” *Genome Biology and Evolution* 10, no. 8 (August 1, 2018): 2010–16, doi:10.1093/gbe/evy169.
23. Zhen Shi et al., “Heterogeneous Ribosomes Preferentially Translate Distinct Subpools of mRNAs Genome-Wide,” *Molecular Cell* 67, no. 1 (July 6, 2017): 71–83, doi:10.1016/j.molcel.2017.05.021.
24. Jeffrey A. Hussmann, Hendrick Osadnik, and Carol A. Gross, “Ribosomal Architecture: Constraints Imposed by the Need for Self-Production,” *Current Biology* 27, no. 16 (August 21, 2017): R798–R800, doi:10.1016/j.cub.2017.06.080.
25. J. D. Watson and Francis Crick, “The Structure of DNA,” *Cold Spring Harbor Symposia on Quantitative Biology* 18 (1953): 123–31, doi:10.1101/sqb.1953.018.01.020.
26. Shoko Kimura et al., “Template-Dependent Nucleotide Addition in the Reverse (3′–5′) Direction by Thg1-like Protein,” *Science Advances* 2, no. 3 (March 25, 2016): e1501397, doi:10.1126/sciadv.1501397.
27. James E. Graham, Kenneth J. Marians, and Stephen C. Kowalczykowski, “Independent and Stochastic Action of DNA Polymerases in the Replisome,” *Cell* 169, no. 7 (June 15, 2017): 1201–13, doi:10.1016/j.cell.2017.05.041.
28. J. William Schopf, “When Did Life Begin?” in *Life’s Origin: The Beginnings of Biological Evolution*, ed. J. William Schopf (Berkeley, CA: University of California Press, 2002), 163.
29. Detlef D. Leipe, L. Aravind, and Eugene V. Koonin, “Did DNA Replication Evolve Twice Independently?,” *Nucleic Acids Research* 27, no. 17 (September 1, 1999): 3389–401, doi:10.1093/nar/27.17.3389.

Chapter 7: Cell Membranes

1. S. J. Singer and Garth L. Nicolson, “The Fluid Mosaic Model of the Structure of Cell Membranes,” *Science* 175, no. 4023 (February 18, 1972): 720–31, doi:10.1126/science.175.4023.720.
2. G. Vereb et al., “Dynamic, Yet Structured: The Cell Membrane Three Decades after the Singer-Nicolson Model,” *Proceedings of the National Academy of Sciences, USA* 100, no. 14 (July 8, 2003): 8053–58, doi:10.1073/pnas.1332550100; Donald M. Engelman, “Membranes Are More Mosaic Than Fluid,” *Nature* 438 (December 1, 2005): 578–80, doi:10.1038/nature04394.
3. Miles D. Houslay and Keith K. Stanley, *Dynamics of Biological Membranes: Influence on Synthesis, Structure and Function* (New York: John Wiley & Sons, 1982), 152–205.
4. Philippe F. Devaux, “Static and Dynamic Lipid Asymmetry in Cell Membranes,” *Biochemistry* 30, no. 5 (February 5, 1991): 1163–73, doi:10.1021/bi00219a001.
5. Houslay and Stanley, *Dynamics of Biological Membranes*, 152–205.
6. Houslay and Stanley, *Dynamics of Biological Membranes*, 98–105.
7. Vereb et al., “Dynamic, Yet Structured,” 8053–58; Engelman, “Membranes Are More Mosaic,” 578–80.
8. Kai Simons and Elina Ikonen, “Functional Rafts in Cell Membranes,” *Nature* 387 (June 5, 1997): 569–72, doi:10.1038/42408; D. A. Brown and E. London, “Functions of Lipid Rafts in Biological Membranes,” *Annual Review of Cell and Developmental Biology* 14 (November 1998): 111–36, doi:10.1146/annurev.cellbio.14.1.111.
9. Danilo D. Lasic, “The Mechanism of Vesicle Formation,” *Biochemical Journal* 256, no. 1 (November 15, 1988): 1–11, id. 3066342, doi:10.1042/bj2560001.
10. Lasic, “Mechanism of Vesicle Formation,” 1–11.
11. For example, see Barry R. Lentz, Tamra J. Carpenter, and Dennis R. Alford, “Spontaneous Fusion of Phosphatidylcholine Small Unilamellar Vesicles in the Fluid Phase,” *Biochemistry* 26, no. 17 (August 25, 1987): 5389–97, doi:10.1021/bi00391a026.
12. N. L. Gershfeld, “The Critical Unilamellar Lipid State: A Perspective for Membrane Bilayer Assembly,” *Biochimica et Biosphysica Acta* 988, no. 3 (December 6, 1989): 335–50, doi:10.1016/0304-4157(89)90009-9.
13. For example, see N. L. Gershfeld et al., “Critical Temperature for Unilamellar Vesicle Formation in Dimyristoylphosphatidylcholine Dispersions from Specific Heat Measurements,” *Biophysical Journal* 65, no. 3 (September 1, 1993): 1174–79, doi:10.1016/S0006-3495(93)81157-3.
14. N. L. Gershfeld, “Spontaneous Assembly of a Phospholipid Bilayer as a Critical Phenomenon: Influence of Temperature, Composition, and Physical State,” *Journal of Physical Chemistry* 93, no. 13 (June 1, 1989): 5256–61, doi:10.1021/j100350a043.
15. For example, see Lionel Ginsberg, Daniel L. Gilbert, and N. L. Gershfeld, “Membrane Bilayer Assembly in Neural Tissue of Rat and Squid as a Critical Phenomenon: Influence of Temperature and Membrane Proteins,” *Journal of Membrane Biology* 119 (January 1991): 65–73, doi:10.1007/BF01868541.

16. For example, see K. E. Tremper and N. L. Gershfeld, “Temperature Dependence of Membrane Lipid Composition in Early Blastula Embryos of *Lytechinus pictus*: Selective Sorting of Phospholipids into Nascent Plasma Membranes,” *Journal of Membrane Biology* 171 (September 1999): 47–53, doi:10.1007/s002329900557.
17. For example, see A. J. Jin et al., “A Singular State of Membrane Lipids at Cell Growth Temperatures,” *Biochemistry* 38, no. 40 (October 1, 1999): 13275–78, doi:10.1021/bi9912084.
18. For example, see N. L. Gershfeld and M. Murayama, “Thermal Instability of Red Blood Cell Membrane Bilayers: Temperature Dependence of Hemolysis,” *Journal of Membrane Biology* 101 (December 1988): 67–72, doi:10.1007/BF01872821.
19. J. N. Israelachvili, S. Marčelja, and R. G. Horn, “Physical Principles of Membrane Organization,” *Quarterly Reviews of Biophysics* 13, no. 2 (May 1980): 121–200, doi:10.1017/S0033583500001645.
20. William R. Hargreaves and David W. Deamer, “Liposomes from Ionic, Single-Chain Amphiphiles,” *Biochemistry* 17, no. 18 (September 5, 1978): 3759–68, doi:10.1021/bi00611a014.
21. Charles L. Apel, David W. Deamer, and Michael N. Mautner, “Self-Assembled Vesicles of Monocarboxylic Acids and Alcohols: Conditions for Stability and for the Encapsulation of Biopolymers,” *Biochimica et Biophysica Acta* 1559, no. 1 (February 10, 2002): 1–9, doi:10.1016/s0005-2736(01)00400-x.
22. David W. Deamer and R. M. Pashley, “Amphiphilic Components of the Murchison Carbonaceous Chondrite: Surface Properties and Membrane Formation,” *Origins of Life and Evolution of the Biosphere* 19, no. 1 (1989): 21–38, doi:10.1007/BF01808285; David W. Deamer, “Boundary Structures Are Formed by Organic Components of the Murchison Carbonaceous Chondrite,” *Nature* 317 (October 31, 1985): 792–94, doi:10.1038/317792a0.
23. Hargreaves and Deamer, “Liposomes,” 3759–68; Apel, Deamer, and Mautner, “Self-Assembled Vesicles,” 1–9.
24. Hargreaves and Deamer, “Liposomes,” 3759–68; Apel, Deamer, and Mautner, “Self-Assembled Vesicles,” 1–9.
25. Trishool Namani and David W. Deamer, “Stability of Model Membranes in Extreme Environments,” *Origins of Life and Evolution of Biospheres* 38, no. 4 (August 2008): 329–41, doi:10.1007/s11084-008-9131-8.
26. S. E. Maurer et al., “Chemical Evolution of Amphiphiles: Glycerol Monoacyl Derivatives Stabilize Plausible Prebiotic Membranes,” *Astrobiology* 9, no. 10 (December 2009): 979–87, doi:10.1089/ast.2009.0384.
27. Bernd R. T. Simoneit, Ahmed I. Rushdi, and David W. Deamer, “Abiotic Formation of Acylglycerols under Simulated Hydrothermal Conditions and Self-Assembly Properties of Such Lipid Products,” *Advances in Space Research* 40, no. 11 (2007): 1649–56, doi:10.1016/j.asr.2007.07.034.
28. Sheref S. Mansy et al., “Template-Directed Synthesis of a Genetic Polymer in a Model Protocell,” *Nature* 454 (July 3, 2008): 122–25, doi:10.1038/nature07018; David W. Deamer, “How Leaky Were Primitive Cells?” *Nature* 454 (July 3, 2008): 37–38, doi:10.1038/454037a.
29. Gordon Sproul, “Abiogenic Syntheses of Lipoamino Acids and Lipopeptides and Their Prebiotic Significance,” *Origins of Life and Evolution of Biospheres* 45, no. 4 (December 2015): 427–37, doi:10.1007/s11084-015-9451-4.
30. MaRosa Infante, Aurora Pinazo, and Joan Seguer, “Non-Conventional Surfactants from Amino Acids and Glycolipids: Structure, Preparation and Properties,” *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 123–124 (May 15, 1997): 49–70, doi:10.1016/S0927-7757(96)03793-4; Michael Ambuehl et al., “Configurational Changes Accompanying Vesiculation of Mixed Single-Chain Amphiphiles,” *Langmuir* 9, no. 1 (January 1, 1993): 36–38, doi:10.1021/la00025a011.
31. Hiroyuki Fukuda et al., “Bilayer-Forming Ion Pair Amphiphiles from Single-Chain Surfactants,” *Journal of the American Chemical Society* 112, no. 4 (February 1, 1990): 1635–37, doi:10.1021/ja00160a057; S. A. Safran et al., “Spontaneous Vesicle Formation by Mixed Surfactants,” *Progress in Colloid and Polymer Science* 84 (1991): 3–7, doi:10.1007/BFb0115925.
32. S. M. Gruner et al., “Lipid Polymorphism: The Molecular Basis of Nonbilayer Phases,” *Annual Review of Biophysics and Biophysical Chemistry* 14 (June 1985): 211–38, doi:10.1146/annurev.bb.14.060185.001235.
33. S. M. Gruner, “Intrinsic Curvature Hypothesis for Biomembrane Lipid Composition: A Role for Nonbilayer Lipids,” *Proceedings of the National Academy of Sciences, USA* 82, no. 11 (June 1, 1985): 3665–69, doi:10.1073/pnas.82.11.3665; P. R. Cullis and B. de Kruijff, “Lipid Polymorphism and the Functional Roles of Lipids in Biological Membranes,” *Biochimica et Biophysica Acta* 559, no. 4 (December 20, 1979): 399–420, doi:10.1016/0304-4157(79)90012-1.
34. G. Dennis Sprott, “Archaeal Membrane Lipids and Applications,” in *eLS* (Hoboken, NJ: John Wiley & Sons, 2011): doi:10.1002/9780470015902.a0000385.pub3.
35. Parkson Lee-Gau Chong, “Archaebacterial Bipolar Tetraether Lipids: Physico-Chemical and Membrane Properties,” *Chemistry and Physics of Lipids* 163, no. 3 (March 2010): 253–65, doi:10.1016/j.chemphyslip.2009.12.006.
36. Daniel Balleza et al., “Ether- versus Ester-Linked Phospholipid Bilayers Containing Either Linear or Branched Apolar Chains,” *Biophysical Journal* 107, no. 6 (September 16, 2014): 1364–74, doi:10.1016/j.bpj.2014.07.036; S. Deren Guler et al., “Effects of Ether vs. Ester Linkage on Lipid Bilayer Structure and Water Permeability,” *Chemistry and Physics of Lipids* 160, no. 1 (July 2009): 33–44, doi:10.1016/j.chemphyslip.2009.04.003; Antonella Caforio and Arnold J. M. Driessen, “Archaeal Phospholipids: Structural Properties and Biosynthesis,” *Biochimica et Biophysica Acta* 1862, no. 11 (November 2017): 1325–39, doi:10.1016/j.bbalip.2016.12.006.
37. Cullis and de Kruijff, “Lipid Polymorphism,” 399–400.
38. W. Dowhan, “Molecular Basis for Membrane Phospholipid Diversity: Why Are There So Many Lipids?,” *Annual Review of Biochemistry* 66 (1997): 199–232, doi:10.1146/annurev.biochem.66.1.199.
39. Houslay and Stanley, *Dynamics of Biological Membranes*, 51–65.
40. Dowhan, “Membrane Phospholipid Diversity,” 199–232.

41. Giuseppe Paradies et al., “Functional Role of Cardiolipin in Mitochondrial Bioenergetics,” *Biochimica et Biophysica Acta—Bioenergetics* 1837, no. 4 (April 2014): 408–17, doi:10.1016/j.bbabio.2013.10.006.
42. Anna L. Duncan, Alan J. Robinson, and John E. Walker, “Cardiolipin Binds Selectively but Transiently to Conserved Lysine Residues in the Rotor of Metazoan ATP Synthases,” *Proceedings of the National Academy of Sciences, USA* 113, no. 31 (August 2, 2016): 8687–92, doi:10.1073/pnas.1608396113.
43. Dowhan, “Membrane Phospholipid Diversity,” 199–232.

Chapter 8: Energy-Harvesting Pathways

1. David Marchese, “The Lion in Johnny Winter: A Tribute to the Guitar Icon,” *Rolling Stone*, July 17, 2014, rollingstone.com/music/music-news/the-lion-in-johnny-winter-a-tribute-to-the-guitar-icon-242043.
2. Enrique Meléndez-Hevia et al., “Theoretical Approaches to the Evolutionary Optimization of Glycolysis—Chemical Analysis,” *European Journal of Biochemistry* 244, no. 2 (March 1997): 527–43, doi:10.1111/j.1432-1033.1997.t01-1-00527.x.
3. Arren Bar-Even et al., “Rethinking Glycolysis: On the Biochemical Logic of Metabolic Pathways,” *Nature Chemical Biology* 8 (June 2012): 509–17, doi:10.1038/nchembio.971.
4. Bar-Even et al., “Rethinking Glycolysis,” 509–17.
5. Bar-Even et al., “Rethinking Glycolysis,” 509–17.
6. Bar-Even et al., “Rethinking Glycolysis,” 509–17.
7. Bar-Even et al., “Rethinking Glycolysis,” 509–17.
8. Bar-Even et al., “Rethinking Glycolysis,” 509–17.
9. Reinhart Heinrich et al., “Theoretical Approaches to the Evolutionary Optimization of Glycolysis: Thermodynamic and Kinetic Constraints,” *European Journal of Biochemistry* 243, nos. 1–2 (January 1997): 191–201, doi:10.1111/j.1432-1033.1997.0191a.x; Oliver Ebenhöh and Reinhart Heinrich, “Evolutionary Optimization of Metabolic Pathways. Theoretical Reconstruction of the Stoichiometry of ATP and NADH Producing Systems,” *Bulletin of Mathematical Biology* 63, no. 1 (January 2001): 21–55, doi:10.1006/bulm.2000.0197.
10. Bar-Even et al., “Rethinking Glycolysis,” 509–17; Meléndez-Hevia et al., “Evolutionary Optimization of Glycolysis,” 527–43.
11. Bar-Even et al., “Rethinking Glycolysis,” 509–17; Melendez-Hevia et al., “Evolutionary Optimization of Glycolysis,” 527–43.
12. Meléndez-Hevia et al., “Evolutionary Optimization of Glycolysis,” 527–43.
13. For example, see Ebenhöh and Heinrich, “Evolutionary Optimization of Metabolic Pathways,” 21–55; Steven J. Court, Bartlomiej Waclaw, and Rosalind J. Allen, “Lower Glycolysis Carries a Higher Flux than Any Biochemically Possible Alternative,” *Nature Communications* 6 (September 29, 2015): id. 8427, doi:10.1038/ncomms9427.
14. Ebenhöh and Heinrich, “Evolutionary Optimization of Metabolic Pathways,” 21–55.
15. Court, Waclaw, and Allen, “Lower Glycolysis.”
16. Meléndez-Hevia et al., “Evolutionary Optimization of Glycolysis,” 527–43.
17. Avi Flamholz et al., “Glycolytic Strategy as a Tradeoff between Energy Yield and Protein Cost,” *Proceedings of the National Academy of Sciences, USA* 110, no. 24 (June 11, 2013): 10039–44, doi:10.1073/pnas.1215283110.
18. Ebenhöh and Heinrich, “Evolutionary Optimization of Metabolic Pathways,” 21–55.
19. Elad Noor et al., “Central Carbon Metabolism as a Minimal Biochemical Walk between Precursors for Biomass and Energy,” *Molecular Cell* 39, no. 5 (September 10, 2010): 809–20, doi:10.1016/j.molcel.2010.08.031.
20. Enrique Meléndez-Hevia, Thomas G. Waddell, and Marta Cascante, “The Puzzle of the Krebs Citric Acid Cycle: Assembling the Pieces of Chemically Feasible Reactions, and Opportunism in the Design of Metabolic Pathways during Evolution,” *Journal of Molecular Evolution* 43 (September 1996): 293–303, doi:10.1007/bf02338838.
21. Bar-Even et al., “Rethinking Glycolysis,” 509–17.
22. Arren Bar-Even et al., “Hydrophobicity and Charge Shape Cellular Metabolite Concentrations,” *PLOS Computational Biology* 7, no. 10 (October 6, 2011): e1002166, doi:10.1371/journal.pcbi.1002166.
23. Harold J. Morowitz et al., “The Origin of Intermediary Metabolism,” *Proceedings of the National Academy of Sciences, USA* 97, no. 14 (July 5, 2000): 7704–8, doi:10.1073/pnas.110153997.
24. Kamila B. Muchowska, Sreejith J. Varma, and Joseph Moran, “Synthesis and Breakdown of Universal Metabolic Precursors Promoted by Iron,” *Nature* 569 (May 2, 2019): 104–7, doi:10.1038/s41586-019-1151-1; Robert Pascal, “A Possible Non-biological Reaction Framework for Metabolic Processes on Early Earth,” *Nature* 569 (May 1, 2019): 47–49, doi:10.1038/d41586-019-01322-3.
25. Eric Smith and Harold J. Morowitz, “Universality in Intermediary Metabolism,” *Proceedings of the National Academy of Sciences, USA* 101, no. 36 (September 7, 2004): 13168–73, doi:10.1073/pnas.0404922101.
26. Markus A. Keller, Alexandra V. Turchyn, and Markus Ralser, “Non-enzymatic Glycolysis and Pentose Phosphate Pathway-Like Reactions in a Plausible Archean Ocean,” *Molecular Systems Biology* 10, no. 4 (April 25, 2014): 725, doi:10.1002/msb.20145228.
27. Keller, Turchyn, and Ralser, “Non-enzymatic Glycolysis,” 725.
28. John Prebble, “Peter Mitchell and the Ox Phos Wars,” *Trends in Biochemical Sciences* 27, no. 4 (April 1, 2002): 209–12, doi:10.1016/S0968-0004(02)02059-5.
29. Leslie E. Orgel, “Are You Serious, Dr Mitchell?” *Nature* 402, no. 17 (November 4, 1999): doi:10.1038/46903.

30. Nick Lane, John F. Allen, and William Martin, “How Did LUCA Make a Living? Chemiosmosis in the Origin of Life,” *BioEssays* 32, no. 4 (March 26, 2010): 271–80, doi:10.1002/bies.200900131.
31. Nick Lane, “Why Are Cells Powered by Proton Gradients?,” *Nature Education* 3, no. 9 (2010): 18.
32. Nick Lane, “Bioenergetic Constraints on the Evolution of Complex Life,” *Cold Spring Harbor Perspectives in Biology* 6, no. 5 (May 2014): a015982, doi:10.1101/cshperspect.a015982.

Chapter 9: Implications of the Biochemical Anthropic Principle

1. David Deamer, “A Giant Step towards Artificial Life?,” *TRENDS in Biotechnology* 23, no. 7 (July 1, 2005): 336–338, doi:10.1016/j.tibtech.2005.05.008.
2. Arren Bar-Even et al., “Hydrophobicity and Charge Shape Cellular Metabolite Concentrations,” *PLOS Computational Biology* 7, no. 10 (October 6, 2011): e1002166, doi:10.1371/journal.pcbi.1002166.
3. Bar-Even et al., “Hydrophobicity and Charge Shape.”
4. Melissa Ilardo et al., “Adaptive Properties of the Genetically Encoded Amino Acid Alphabet Are Inherited from Its Subsets,” *Scientific Reports* 9 (August 28, 2019): 12468, doi:10.1038/s41598-019-47574-x.
5. Ilardo et al., “Adaptive Properties.”
6. Tokyo Institute of Technology, “Scientists Find Biology’s Optimal ‘Molecular Alphabet’ May Be Preordained,” *ScienceDaily* (September 10, 2019), sciencedaily.com/releases/2019/09/190910080017.htm.
7. Clemens Richert, “Prebiotic Chemistry and Human Intervention,” *Nature Communications* 9 (December 12, 2018): 5177, doi:10.1038/s41467-018-07219-5.
8. Richert, “Prebiotic Chemistry,” 5177.
9. Simon Conway Morris, *Life’s Solution: Inevitable Humans in a Lonely Universe* (Cambridge: Cambridge University Press, 2003), 41.
10. Leonard M. Adleman, “Computing with DNA,” *Scientific American* 279, no. 2 (August 1998): 54–61, doi:10.1038/scientificamerican0898-54.