

WHAT'S GOTTEN INTO YOU

The Story of
Your Body's Atoms,
from the Big Bang
Through Last Night's Dinner

Dan Levitt



HARPER

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NOTES

Epigraph

- vii “We are an example”: Quoted in Cott, “The Cosmos: An Interview with Carl Sagan.”

Introduction: \$1942.29 in the Bank

- xii thirty trillion cells: Sender, Fuchs, and Milo, “Revised Estimates for the Number of Human and Bacteria Cells in the Body,” 9.
- xii over a hundred trillion atoms: Milo and Phillips, *Cell Biology by the Numbers*, 68.
- xii a billion times more atoms than all the grains of sand: Blatner, *Spectrums*, 20.
- xii a cool \$1,942.29: Calculations of the value of the elements in the human body vary wildly. Here is how \$1,942.29 was calculated. The mass of each element in the body comes from *Nature’s Building Blocks: An A–Z Guide to the Elements*, by John Emsley. The cost of each element is from the website Chemi-cool.com. Of course, the actual costs will vary—depending, for instance, on whether you plan to make water from scratch or buy it from the supermarket.

Chapter 1: Happy Birthday to Everyone: The Priest Who Discovered the Beginning of Time

- 3 “All great truths”: Shaw, *Annajanska, the Bolshevik Empress*, 139.
- 3 Central Hall, Westminster: The *Times*, “The British Association: Evolution of the Universe.”
- 4 “primeval atom”: Lemaître, “Contributions to a British Association Discussion on the Evolution of the Universe,” 706.
- 4 “who are immeasurably beyond”: Barnes, “Contributions to a British Association Discussion on the Evolution of the Universe,” 722.
- 4 cycling trip: Mitton, “The Expanding Universe of Georges Lemaître,” 28.
- 4 outdated single-loading rifles: Mitton, “Georges Lemaître and the Foundations of Big Bang Cosmology,” 4.
- 5 “The madness of it”: Deprit, “Monsignor Georges Lemaître,” 365.
- 5 He lacked, it seemed: Deprit, “Monsignor,” 366.
- 5 he somehow found the concentration: Lambert, *The Atom of the Universe: The Life and Work of Georges Lemaître*, 56–57.
- 5 What was the universe: Lambert, “Georges Lemaître: The Priest Who Invented the Big Bang,” 11.
- 5 “two ways of arriving”: Aikman, “Lemaître Follows Two Paths to Truth.”
- 5 Amis de Jésus: Lambert, “Georges Lemaître,” 16.

Notes

- 6 “wonderfully quick and clear-sighted”: Kragh, “The Wildest Speculation of All”: Lemaître and the Primeval-Atom Universe,” 24.
- 6 “‘island universes’ similar to our own”: *New York Times*, “Finds Spiral Nebulae Are Stellar Systems: Dr. Hubbell [*sic*] Confirms View That They Are ‘Island Universes’ Similar to Our Own.”
- 6 the latest measurements taken: Mitton, “The Expanding Universe,” 29–30.
- 7 the space between them was actually expanding: Although the empty space between galaxies is expanding, the galaxies themselves and the matter within them are not. That is because the gravitational attraction between the clusters of matter in galaxies is much stronger than the force that is pulling space, and them, apart.
- 7 in a little-known Belgian periodical: Kragh, “The Wildest Speculation,” 34.
- 7 As he strolled through: Lambert, “Einstein and Lemaître: Two Friends, Two Cosmologies.”
- 7 He hated it: Frenkel and Grib, “Einstein, Friedmann, Lemaître,” 13.
- 8 “Your calculations”: Deprit, “Monsignor,” 370.
- 8 began speaking with Piccard: Lemaître, “My Encounters with A. Einstein.”
- 8 embarrassed to find: Farrell, *The Day without Yesterday: Lemaître, Einstein, and the Birth of Modern Cosmology*, 97.
- 9 “disintegration”: Lemaître, “Contributions,” 706.
- 9 “The evolution of the universe”: Lemaître, *The Primeval Atom: An Essay on Cosmogony*, 78.
- 9 “Bart, I’ve had a funny idea”: DeVorkin, AIP oral history interview with Bart Bok.
- 9 “Out of a single bursting atom”: Menzel, “Blast of Giant Atom Created Our Universe.”
- 9 “an example of speculation run mad”: Kragh, “The Wildest Speculation,” 35–36.
- 10 in 1978: Godart, “The Scientific Work of Georges Lemaître,” 395.
- 10 “Physics provides a veil”: Quoted in Lambert, “Georges Lemaître,” 16.
- 10 “There is no conflict”: Aikman, “Lemaître Follows.”
- 10 “biggest blunder”: O’Raifeartaigh and Mitton, “Interrogating the Legend of Einstein’s ‘Biggest Blunder.’” While some historians have questioned whether Einstein actually said this, there are those who believe that he did.
- 10 “This is the most beautiful”: Aikman, “Lemaître Follows.”
- 11 “the Catastrophe to begin”: Lemaître, *The Primeval Atom*, vi.
- 11 “The hypothesis that all matter”: Cooper, *Origins of the Universe*.
- 11 “the Big Bang man”: Lambert, “Georges Lemaître,” 17.
- 12 “It is the same way that”: Author interview with Avi Loeb, Harvard Smithsonian, August 2018.
- 13 gravitational echoes of the Big Bang: Webb, “Listening for Gravitational Waves from the Birth of the Universe.”

Notes

Chapter 2: “That’s Funny”: What the Eye Can Never See

- 15 But many physicists were dubious: Rhodes, *The Making of the Atomic Bomb*, 30–31.
- 16 “Atoms and molecules . . . from their very nature”: Blackmore, *Ernst Mach*, 321.
- 17 a hundred thousand times smaller: Close, *Particle Physics: A Very Short Introduction*, 14.
- 17 thick metal boxes: De Angelis, “Atmospheric Ionization and Cosmic Rays,” 3.
- 18 deep into caves: Gbur, “Paris: City of Lights and Cosmic Rays.”
- 18 Enlisting the help: Bertolotti, *Celestial Messengers: Cosmic Rays: The Story of a Scientific Adventure*, 36.
- 18 a twelve-story orange-and-black: Kraus, “A Strange Radiation from Above,” 20.
- 18 squeezed himself into: Part of Hess’s account is translated into English in Steinmaurer, “Erinnerungen an V. F. Hess, Den Entdecker der Kosmischen Strahlung, und an Die ersten Jahre des Betriebes des Hafelekar-Labors.”
- 19 “an inner joy is felt”: “The *Zenith* Tragedy”; and Oliveira, “Martyrs Made in the Sky.”
- 19 Wasn’t it more likely: Ziegler, “Technology and the Process of Scientific Discovery,” 950.
- 20 especially fierce opponent: Walter, “From the Discovery of Radioactivity to the First Accelerator Experiments,” 28.
- 20 until Hess bitterly objected: De Maria, Ianniello, and Russo, “The Discovery of Cosmic Rays,” 178.
- 21 “the most original and wonderful instrument”: Quoted in *Nobel Lectures Physics: Including Presentation Speeches and Laureates’ Biographies, 1922–1941*, 215.
- 21 Fearing others would think him crazy: Pais, *Inward Bound: Of Matter and Forces in the Physical World*, 38.
- 21 when cathode rays: Two years later, J. J. Thomson would discover that the cathode “rays” inside the glass tube were actually streams of electrons.
- 21 “Nearly every professor”: Pais, *Inward Bound*, 39.
- 21 He was startled to see: Crowther, *Scientific Types*, 38.
- 21 Wilson was ecstatic: BBC Interview with Wilson in transcript of the BBC documentary “Wilson of the Cloud Chamber.”
- 22 “little wisps and threads”: *Nobel Lectures Physics*, 216.
- 22 insisted that Anderson: Anderson, *The Discovery*, 25–26.
- 22 the tracks must instead be from positively charged protons: Anderson, *The Discovery*, 29–30.
- 22 None of the famous gods: Hanson, “Discovering the Positron (I),” 199.
- 23 almost four thousand positrons a day: Sundermier, “The Particle Physics of You.”
- 23 “Who ordered that?”: Close, Marten, and Sutton, *The Particle Odyssey: A Journey to the Heart of Matter*, 69.

Notes

- 24 radium-fortified soap: Rentetzi, *Trafficking Materials and Gendered Experimental Practices*, 2; and Miklós, “Seriously Scary Radioactive Products from the 20th Century.”
- 24 Could she use a photographic plate to detect: Sime, “Marietta Blau: Pioneer of Photographic Nuclear Emulsions and Particle Physics,” 7.
- 25 That was impossible: Rentetzi, AIP oral history interview with Leopold Halpern.
- 25 generously offered help: Rentetzi, AIP oral history interview with Leopold Halpern.
- 25 an early member: Galison, “Marietta Blau: Between Nazis and Nuclei,” 44.
- 25 Wambacher began an affair: Sime, “Marietta Blau,” 14.
- 26 up to twelve smaller particles: Rosner and Strohmaier, *Marietta Blau, Stars of Disintegration*, 159.
- 26 taking her newest plates: Rentetzi, “Blau, Marietta,” 301.
- 26 seized her photographic plates: Rentetzi, AIP oral history interview with Leopold Halpern.
- 27 she was embittered: Rentetzi, AIP oral history interview with Leopold Halpern.
- 28 130,000 miles in just four-fifths of a second: Plumb, “Brookhaven Cosmotron Achieves the Miracle of Changing Energy Back into Matter.”
- 28 less than a billionth of a second: Close, Marten, and Sutton, *The Particle Odyssey*, 13.
- 28 Joy turned to bafflement: Riordan, *The Hunting of the Quark: A True Story of Modern Physics*, 69.
- 28 “If I could remember the names”: Quoted in Riordan, *The Hunting*, 69.
- 29 At age three: Johnson, *Strange Beauty: Murray Gell-Mann and the Revolution in Twentieth-Century Physics*, 35.
- 29 “on first acquaintance”: Glashow, “Book Review of *Strange Beauty: Murray Gell-Mann and the Revolution in Twentieth-Century Physics*,” 582.
- 30 Perhaps it would finally lead: Bernstein, *A Palette of Particles*, 95.
- 30 Gell-Mann was apprehensive: Johnson, *Strange Beauty*, 194.
- 30 Collegially, they shared: Johnson, *Strange Beauty*, 208.
- 30 Long Island housewives: Crease and Mann, *The Second Creation: Makers of the Revolution in Twentieth-Century Physics*, 275.
- 30 But in the 97,025th: Johnson, *Strange Beauty*, 217.
- 31 “That would be a funny quirk”: Riordan, *The Hunting*, 101.
- 31 *What the hell, why not?*: Crease and Mann, *The Second Creation*, 281.
- 31 a useful mathematical fiction: Johnson, *Strange Beauty*, 283–84.
- 32 more open to publishing “crazy” ideas: Crease and Mann, *The Second Creation*, 284.
- 32 the barriers: Charitos, “Interview with George Zweig.”

Notes

- 32 labeled him a charlatan: Zweig, “Origin of the Quark Model,” 36.
32 a million times smaller than a grain of sand: Butterworth, “How Big Is a Quark?”
32 “they [had] begun opening”: Sullivan, “Subatomic Tests Suggest a New Layer of Matter.”
33 a billion billion billion times: Chu, “Physicists Calculate Proton’s Pressure Distribution for First Time.”
33 You could fit all of humanity: Sundermier, “The Particle Physics of You.”
35 a trillion quadrillion H-bombs: Cottrell, *Matter: A Very Short Introduction*, 127.

Chapter 3: The Best Man at Harvard: The Woman Who Changed How We See the Stars

- 36 “There are three stages”: Hoyle, *Home Is Where the Wind Blows: Chapters from a Cosmologist’s Life*, 154.
36 “I saw an abyss opening”: Payne-Gaposchkin, *Cecilia Payne-Gaposchkin: An Autobiography and Other Recollections*, 124.
37 She prayed for high marks: Payne-Gaposchkin, *Cecilia Payne-Gaposchkin*, 97.
37 “prostituting her gifts”: Payne-Gaposchkin, *Cecilia Payne-Gaposchkin*, 98.
37 expected to become a botanist: Payne-Gaposchkin, *Cecilia Payne-Gaposchkin*, 102.
37 “like a nervous breakdown”: Payne-Gaposchkin, *Cecilia Payne-Gaposchkin*, 117–18.
38 she was eager to tackle: Gingerich, AIP oral history interview with Cecilia Payne-Gaposchkin.
40 thousands of individual stars: Moore, *What Stars Are Made Of: The Life of Cecilia Payne-Gaposchkin*, 172.
40 “As you look at it”: Author interview with Owen Gingerich, Harvard University, February 2018.
40 “utter bewilderment”: Payne-Gaposchkin, *Cecilia Payne-Gaposchkin*, 163.
40 “Miss Payne? You’re very brave”: Payne-Gaposchkin, *Cecilia Payne-Gaposchkin*, 165.
41 “clearly impossible”: Payne-Gaposchkin, *Cecilia Payne-Gaposchkin*, 19.
41 There were strong reasons: Gingerich, “The Most Brilliant Ph.D. Thesis Ever Written in Astronomy,” 11.
41 “His word could”: Payne-Gaposchkin, *Cecilia Payne-Gaposchkin*, 201.
41 “almost certainly not real”: Payne-Gaposchkin, *Cecilia Payne-Gaposchkin*, 5.
41 told the writer Donovan Moore: Moore, *What Stars Are Made Of*, 183.
41 Russell himself: DeVorkin, *Henry Norris Russell: Dean of American Astronomers*, 213–16; and Gingerich, “The Most Brilliant Ph.D. Thesis Ever Written in Astronomy,” 13–14.

Notes

- 41 “the best man at Harvard”: Payne-Gaposchkin, *Cecilia Payne-Gaposchkin*, 184.
41 would not be listed: Payne-Gaposchkin, *Cecilia Payne-Gaposchkin*, 26.
42 offended by the “stupidity”: Hoyle, *The Small World of Fred Hoyle: An Autobiography*, 72.
42 When he was not “ill”: Hoyle, *The Small World*, 64.
42 “one of the most innovative”: Couper and Henbest, *The History of Astronomy*, 217.
42 “the most creative and original”: Martin Rees quoted in Livio, *Brilliant Blunders: From Darwin to Einstein—Colossal Mistakes by Great Scientists That Changed Our Understanding of Life and the Universe*, 219.
42 “in less time than it takes”: Livio, *Brilliant Blunders*, 180.
43 nowhere near hot enough: Hoyle, *Home Is Where*, 150.
43 top-secret meeting: Mitton, *Fred Hoyle: A Life in Science*, 99.
44 A nighttime curfew: Mitton, *Fred Hoyle*, 104–5.
44 vastly more heat: Gregory, *Fred Hoyle’s Universe*, 31.
44 trying to glean: Hoyle, *Home Is Where*, 229.
44 When a star ran out of fuel: Hoyle, *Home Is Where*, 230.
45 actually be hot enough: Mitton, *Fred Hoyle*, 200.
46 almost 23 percent: Emsley, *Nature’s Building Blocks: An A–Z Guide to the Elements*, 111.
46 “Here was this funny little man”: Weiner, AIP oral history interview with William Fowler.
46 like a prisoner in a dock: Hoyle, *Home Is Where*, 265.
46 After several months: In *Home Is Where the Wind Blows*, Hoyle writes that the wait was ten days, but according to his biographer, Simon Mitton, Hoyle heard the results several months later.
48 less than 1 percent: Emsley, *Nature’s Building Blocks*, 112.
48 heavier than iron on Earth: Uranium, with the atomic number 92, is the heaviest element that exists naturally on Earth.
49 as a hundred billion suns: Gribbin and Gribbin, *Stardust: Supernovae and Life—the Cosmic Connection*, 156.
49 newly released data: Burbidge, “Sir Fred Hoyle 24 June 1915: 20 August 2001,” 225.
49 Hoyle’s team found evidence: Hoyle, *Home Is Where*, 296–97.
50 27 million degrees: “The Sun,” NASA, <https://www.nasa.gov/sun>.
50 clouds of viruses and bacteria: Horgan, “Remembering Big Bang Basher Fred Hoyle.”

Chapter 4: Catastrophes to Be Thankful For: How to Make a World from Gravity and Dust

- 52 “My own suspicion”: Haldane, *Possible Worlds*, 286.
53 “innocent entertainment”: Wetherill, “The Formation of the Earth from Planetesimals,” 174.

Notes

- 54 someone with the technical skill: Burns, Lissauer, and Makalkin, "Victor
Sergeyevich Safronov (1917–1999)."
- 55 Soviet colleagues were skeptical: E-mail to author from Andrei Makalkin,
Institute of Earth Physics of the Russian Academy of Sciences, May 2018.
- 55 He presented a copy: Author interview with that former graduate student:
astronomer Dale Cruikshank, NASA Ames Research Center, May 2018.
- 55 a groundbreaking program: Wetherill, "Contemplation of Things Past," 17.
- 56 runaway effect: Wetherill, "Contemplation," 19.
- 57 Venus spins backward: Hazen, *The Story of Earth: The First 4.5 Billion Years,
from Stardust to Living Planet*, 45.
- 57 violently assaulted: Fisher, "Birth of the Moon," 63.
- 58 "His contributions are of overwhelming proportion": Wetherill, "Contempla-
tion," 18.
- 58 "first scientist": Gribbin, *The Scientists*, 68.
- 58 far-off magnetic mountains: Hockey et al., "Gilbert, William."
- 61 "As far as I'm concerned": Cooper, "Letter from the Space Center," 50. Co-
oper tells this story beautifully in a series of articles in the *New Yorker* and his
book *Apollo on the Moon*.
- 61 King had helped persuade NASA: Compton, *Where No Man Has Gone Be-
fore*, 52.
- 61 \$25 billion: Wilford, "Moon Rocks Go to Houston; Studies to Begin Today:
Lunar Rocks and Soil Are Flown to Houston Lab."
- 61 scientists were debating whether the massive craters: Corfield, "One Giant
Leap," 50.
- 61 A lunar lander would be swallowed: Powell, "To a Rocky Moon," 200.
- 62 the same alarms: Eyles, "Tales from the Lunar Module Guidance Computer."
- 62 about to set them down: Wagener, *One Giant Leap*, 182.
- 62 Armstrong's pulse doubled: Portree, "The *Eagle* Has Crashed (1966)."
- 63 watched impatiently: King, *Moon Trip: A Personal Account of the Apollo Pro-
gram and Its Science*, 92.
- 63 \$24 billion: Wilford, "Moon Rocks."
- 63 police closed the road: Wilford, "Moon Rocks."
- 63 "a radical group of hippies": King, *Moon Trip*, 101.
- 64 exposing algae: West, "Moon Rocks Go to Experts on Friday."
- 64 with gas masks: Weaver, "What the Moon Rocks Tell Us."
- 65 "I mean, big deal": Author interview with Bill Schopf, UCLA, July 2019.
- 65 as some scientists expected: Cooper, *Apollo on the Moon*, 96–99.
- 65 tunnels and two-thirds of a mile of wire: Marvin, "Gerald J. Wasserburg,"
186.
- 65 the Lunatic Asylum: Hammond, *A Passion to Know: 20 Profiles in Science*,
52–53.
- 66 to a Pasadena bar: Wolchover, "Geological Explorers Discover a Passage to
Earth's Dark Age."

Notes

- 66 “It must in any event”: Tera, Papanastassiou, and Wasserburg, “A Lunar Cataclysm at ~3.95 AE and the Structure of the Lunar Crust,” 725.
- 67 a slight chance that Mercury: Laskar and Gastineau, “Existence of Collisional Trajectories of Mercury, Mars and Venus with the Earth.”
- 68 7,000 degrees Fahrenheit: Interview of Peter Schultz of Brown University in the 2005 documentary “The Violent Past” from *Miracle Planet*.

Chapter 5: Dirty Snowballs and Space Rocks: The Biggest Flood of All Time

- 73 “If there is magic”: Eiseley, *The Immense Journey*, 15.
- 74 “How inappropriate”: Lovelock, “Hands Up for the Gaia Hypothesis,” 102.
- 74 more than a hundred species: LaCapra, “Bird, Plane, Bacteria?”
- 74 aqueous to the core: If you placed your blood vessels—your interior rivers and streams that carry water to your cells—end to end, they would extend fifty thousand miles, about two times the circumference of the globe. Sender, Fuchs, and Milo, “Revised Estimates for the Number of Human and Bacteria Cells in the Body,” 7.
- 74 about 75 percent: Krulwich, “Born Wet, Human Babies Are 75 Percent Water: Then Comes the Drying.”
- 74 same as a banana: USDA FoodData Central website.
- 74 60 percent: Aitkenhead, Smith, and Rowbotham, *Textbook of Anaesthesia*, 417.
- 75 eleven cups of water: Emsley, *Nature’s Building Blocks: An A–Z Guide to the Elements*, 228.
- 75 every 1.5 trillionth of a second: Hoffmann, *Life’s Ratchet: How Molecular Machines Extract Order from Chaos*, 116.
- 75 350 feet per second: Ashcroft, *The Spark of Life: Electricity in the Human Body*, 56.
- 75 If you ever feel foggy: Adan, “Cognitive Performance and Dehydration,” 73.
- 76 penned a book: Von Braun, Whipple, and Ley, *Conquest of the Moon*.
- 76 “For a number of years”: DeVorkin, AIP oral history interview with Fred Whipple.
- 76 better academic opportunities: Marsden, “Fred Lawrence Whipple (1906–2004),” 1452.
- 76 It was undemanding enough: Whipple, “Of Comets and Meteors,” 728.
- 76 as deadly boring as any: Marvin, “Fred L. Whipple,” A199.
- 77 just weeks after: Marsden, “Fred Lawrence Whipple (1906–2004),” 1452.
- 77 “orbit computing business”: DeVorkin, AIP oral history interview with Fred Whipple.
- 77 to check the accuracy: Hughes, “Fred L. Whipple 1906–2004,” 6.35.
- 77 bagged over thirty: Levy, *David Levy’s Guide to Observing and Discovering Comets*, 26.
- 77 orbited the Sun over a thousand times: DeVorkin, AIP oral history interview with Fred Whipple.

Notes

- 78 a half hour to an hour: Whipple, “Of Comets and Meteors,” 728.
78 “what’s happening to comets!”: DeVorkin, AIP oral history interview with Fred Whipple.
79 Whipple’s theory only survived: Calder, *Giotto to the Comets*, 38.
79 flying at 41,000 feet: Cowan, “Scientists Uncover First Direct Evidence of Water in Halley’s Comet: New Way to Study Comets Will Help Yield Clues to Solar System’s Origin.”
79 “Well Fred”: Levy, *The Quest for Comets*, 70.
79 “kamikaze mission”: Quoted in Markham, “European Spacecraft Grazes Comet.”
79 over 40 miles a second: Calder, *Giotto*, 107.
80 62,000 miles away: Calder, *Giotto*, 110.
80 set the half-ton machine wobbling: Calder, *Giotto*, 112.
80 80 percent of the gas: Calder, *Giotto*, 130.
81 “The usual thing you get is”: Author interview with Dave Jewitt, UCLA, January 2018.
82 “It can’t possibly be real”: Couper and Henbest, *The History of Astronomy*, 196.
82 comets from the Kuiper Belt: Harder, “Water for the Rock,” 184.
85 Their simulations appeared to reveal: Morbidelli et al., “Source Regions and Timescales for the Delivery of Water to the Earth.”
86 an immaculately clean desk: Richter et al., “Michael J. Drake (1946–2011).”
86 dust surrounded by water vapor: Drake interview in the National Geographic Channel documentary “Birth of the Oceans.”
87 perhaps several times as much: Jewitt and Young, “Oceans from the Skies,” 39; and author conversation with David Rubie, Universitaet Bayreuth, February 2021.
88 Rain poured down for thousands: Kunzig, *Mapping the Deep: The Extraordinary Story of Ocean Science*, 17–18.
88 “Nothing is without controversy”: Author interview with John Valley, University of Wisconsin–Madison, June 2018.
89 30 to 40 percent of all the gold: Hart, *Gold*, 12.
90 decided to ask Wilde: Valley, “A Cool Early Earth?” 63.
90 Others soon confirmed: At UCLA, Stephen Mojzsis, Mark Harrison, and Robert Pidgeon made a similar finding at roughly the same time.

Chapter 6: The Most Famous Experiment: The Search for the Origin of the Molecules of Life

- 92 “They are good company”: Wald, Nobel Banquet Speech, Nobel Prize in Physiology or Medicine 1967.
93 “the world of the living”: Oparin, *The Origin of Life*. An English-language translation by Ann Synge of Oparin’s original paper appears in the appendix of Bernal, *The Origin of Life*, 206–7.
93 delighted in the fantastic variety: Mikhailov, *Put’ k istinye*, 9–10.

Notes

- 93 single “scientific” worldview: Lazcano, “Alexandr I. Oparin and the Origin of Life,” 215.
- 94 Another 1 percent is ions: Cooper and Hausman, *The Cell*, 44.
- 94 70 percent amino acids: Woodard and White, “The Composition of Body Tissues,” 1214.
- 95 “In living Nature”: Quoted in Hunter, *Vital Forces*, 56.
- 95 “Dead matter cannot become”: Kelvin, *Popular Lectures and Addresses: Geology and General Physics*, II:198.
- 95 “It is mere rubbish”: Quoted in Peretó, Bada, and Lazcano, “Charles Darwin and the Origin of Life,” 396.
- 96 “Who knows,” Helmholtz argued, “whether”: Helmholtz, *Science and Culture: Popular and Philosophical Essays*, 275.
- 96 in contrast to Kursanov, “Sketches to a Portrait of A. I. Oparin,” 4.
- 96 “missing its very first chapter”: Schopf, *Cradle of Life: The Discovery of Earth’s Earliest Fossils*, 112.
- 98 it was photosynthesizing algae: Schopf, *Cradle of Life*, 120–21.
- 98 “wild speculation”: Graham, *Science, Philosophy, and Human Behavior in the Soviet Union*, 73.
- 99 neighboring vacation dachas: Schopf, *Cradle of Life*, 123.
- 99 “imprisoned in Siberia?”: Quoted in Graham, *Science in Russia and the Soviet Union*, 276.
- 100 “All the scientists I know”: Quoted in Shindell, *The Life and Science of Harold C. Urey*, 114.
- 100 someone should try testing: Miller, “The First Laboratory Synthesis of Organic Compounds Under Primitive Earth Conditions,” 230.
- 100 “The first thing he tried”: Henahan, “From Primordial Soup to the Prebiotic Beach: An Interview with the Exobiology Pioneer Dr. Stanley L. Miller.”
- 101 “dungeon”: Davidson, *Carl Sagan: A Life*, 23.
- 101 Urey gave a tour: Sagan, *Conversations with Carl Sagan*, 30.
- 102 “It looks like fly shit”: Bada and Lazcano, “Biographical Memoirs: Stanley L. Miller: 1930–2007,” 18.
- 102 “three feet off the floor”: Wade, “Stanley Miller, Who Examined Origins of Life, Dies at 77.”
- 102 at least eight more: Wills and Bada, *The Spark of Life: Darwin and the Primeval Soup*, 49.
- 103 just the kind that Oparin predicted: Mesler and Cleaves II, *A Brief History of Creation*, 178.
- 103 “if I’d submitted it”: Henahan, “From Primordial Soup to the Prebiotic Beach.”
- 103 “They didn’t take it seriously”: Sagan, *Conversations with Carl Sagan*, 30.
- 103 Even Oparin did not believe: Lazcano and Bada, “Stanley L. Miller (1930–2007),” 374.

Notes

- 104 even a high school student: Henahan, “From Primordial Soup to the Prebiotic Beach.”
- 104 “If God did not”: Mesler and Cleaves II, *A Brief History*, 173.
- 104 “The road ahead is hard”: Oparin, *The Origin of Life*, 252.
- 104 not full of hydrogen, methane, and ammonia: Radetsky, “How Did Life Start?” 78.
- 105 primarily nitrogen, carbon dioxide, and water vapor: Zahnle, Schaefer, and Fegley, “Earth’s Earliest Atmospheres,” 2.
- 105 hundreds of thousands of enzymes: Author interview with Laura Lindsey-Boltz, University of North Carolina, October 2021.
- 107 Townes had published: Townes, “Microwave and Radio-Frequency Resonance Lines of Interest to Radio Astronomy.”
- 107 One graduate student: Townes, “The Discovery of Interstellar Water Vapor and Ammonia at the Hat Creek Radio Observatory,” 82.
- 107 “When he came”: Author interview with Jack Welch, University of California, Berkeley, June 2018.
- 108 “You know it’s not going to work”: Townes, *How the Laser Happened: Adventures of a Scientist*, 65.
- 108 “I got the feeling”: Townes, “The Discovery,” 82.
- 110 when hydrogen cyanide combines: Patel et al., “Common Origins of RNA, Protein and Lipid Precursors in a Cyanosulfidic Protometabolism.”
- 110 “We heard this *ba-boom*”: Interview in video, Jess and Kendrew, “Murchison Meteorite Continues to Dazzle Scientists.”
- 110 punched through the metal roof: Meteoritical Society, “Murchison.”
- 110 methylated spirits: Deamer, *First Life: Discovering the Connections between Stars, Cells, and How Life Began*, 53.
- 111 couldn’t rule contamination out: Sullivan, *We Are Not Alone: The Search for Intelligent Life on Other Worlds*, 114.
- 111 New York City ragweed: Sullivan, *We Are Not Alone*, 123–24.
- 112 they found two more: Schopf, *Major Events in the History of Life*, 17.
- 112 the very same ones: Miller, “The First Laboratory Synthesis of Organic Compounds under Primitive Earth Conditions,” 240.
- 114 forty thousand tons: Brownlee, “Cosmic Dust: Building Blocks of Planets Falling from the Sky,” 166.
- 114 ten to a thousand times the mass: Segré and Lancet, “Theoretical and Computational Approaches to the Study of the Origin of Life,” 94–95.
- 114 fragments might have recombined: Barras, “Formation of Life’s Building Blocks Recreated in Lab.”

Chapter 7: The Greatest Mystery: The Puzzling Origin of the First Cells

- 116 “Life is a cosmic imperative”: de Duve, “The Beginnings of Life on Earth,” 437.

Notes

- 117 failed his qualifying exams: Heap and Gregoriadis, “Alec Douglas Bangham, 10 November 1921–9 March 2010,” 28.
- 117 “reneege”: Bangham, “Surrogate Cells or Trojan Horses: The Discovery of Liposomes,” 1081.
- 118 “Membranes came first”: Deamer, “From ‘Banghasomes’ to Liposomes: A Memoir of Alec Bangham, 1921–2010,” 1309.
- 119 Their lives are “Greek tragedies”: Robert Singer quoted in Albert Einstein College of Medicine press release, “Built-In ‘Self-Destruct Timer’ Causes Ultimate Death of Messenger RNA in Cells.”
- 119 once every million to billion years: Milo and Phillips, *Cell Biology by the Numbers*, 215–16.
- 120 it was easy for him: Echols, *Operators and Promoters: The Story of Molecular Biology and Its Creators*, 215.
- 121 “more and more desperate”: Gitschier, “Meeting a Fork in the Road: An Interview with Tom Cech,” 0624.
- 121 “by desperation to the opposite hypothesis”: Cech interview in Howard Hughes Medical Institute video, *The Discovery of Ribozymes*.
- 121 “I didn’t even know”: Quoted in Dick and Strick, *The Living Universe: NASA and the Development of Astrobiology*, 128.
- 121 “never thought much about it”: Author interview with Thomas Cech, University of Colorado Boulder, September 2021.
- 121 “Unknown to us”: Cech interview in HHMI video, *The Discovery of Ribozymes*.
- 123 would support the theory of plate tectonics: Kaharl, *Water Baby: The Story of Alvin*, 168–69.
- 123 tossed overboard after a shipboard feast: Crane, *Sea Legs: Tales of a Woman Oceanographer*, 112–13.
- 124 “Debra, isn’t the deep ocean”: Kaharl, *Water Baby*, 173.
- 124 He was gazing at clams: Kaharl, *Water Baby*, 173.
- 125 Russian vodka they’d purchased: Ballard, *The Eternal Darkness*, 171.
- 125 “RETURN TO PORT”: Kusek, “Through the Porthole 30 Years Ago,” 141.
- 125 “We all started jumping up and down”: Kaharl, *Water Baby*, 175.
- 126 that lived at high temperatures: Wade, “Meet Luca, the Ancestor of All Living Things.”
- 126 about a year later: Hazen, *Genesis: The Scientific Quest for Life’s Origin*, 98–99.
- 127 “head off”: Hazen, *Genesis*, 109.
- 127 “The vents would”: Miller and Bada, “Submarine Hot Springs and the Origin of Life,” 610.
- 128 “Ideas fly around”: Author interview with Günter Wächtershäuser, December 2018.
- 128 the supposedly essential: Wächtershäuser, “The Origin of Life and Its Methodological Challenge,” 488.
- 130 “The prebiotic broth theory”: Wächtershäuser, “Before Enzymes and Templates: Theory of Surface Metabolism,” 453.

Notes

- 130 “The vent hypothesis is a real loser”: Radetsky, “How Did Life Start?” 82.
- 130 “not relevant to the question”: Lucentini, “Darkness Before the Dawn—of Biology,” 29.
- 130 “paper chemistry”: Bada interview in BBC *Horizon* documentary, “Life Is Impossible.”
- 130 “As far as I’m concerned”: Hagmann, “Between a Rock and a Hard Place.”
- 130 “runaway enthusiasm”: Monroe, “2 Dispute Popular Theory on Life Origin.”
- 131 When we spoke: Author interview with Mike Russell, December 2018.
- 131 origin of life much easier to envision: Lane, *Life Ascending*, 19–23.
- 132 ten million to one hundred million of them: Flamholz, Phillips, and Milo, “The Quantified Cell,” 3498.
- 132 once provided the energy: Lane, *The Vital Question: Why Is Life the Way It Is?* 117–19.
- 134 John Sutherland has found: Wade, “Making Sense of the Chemistry That Led to Life on Earth.”
- 134 “We have got to be open”: Author interview with George Cody, Carnegie Institution for Science, June 2018.
- 134 “if we need a location”: Author interview with Jay Melosh, Purdue University, May 2018.
- 135 higher than 104 degrees: California Institute of Technology press release, “Caltech Geologists Find New Evidence That Martian Meteorite Could Have Harbored Life”; and Weiss et al., “A Low Temperature Transfer of ALH84001 from Mars to Earth.”
- 135 the vacuum of space is not a deal breaker: Nicholson et al., “Resistance of *Bacillus Endospores* to Extreme Terrestrial and Extraterrestrial Environments.”
- 135 have survived a 553-day joyride: Amos, “Beer Microbes Live 553 Days Outside ISS.”
- 135 life certainly existed by 3.5 billion years ago: Knoll, *A Brief History of Earth: Four Billion Years in Eight Chapters*, 81–83.
- 136 Kirschvink has complex additional reasons: See Kirschvink and Weiss, “Mars, Panspermia, and the Origin of Life: Where Did It All Begin?” Additionally, Kirschvink and the biochemist Steve Benner argue that it is difficult to make RNA without the stabilization provided by the chemical borate; and while borate is rare on Earth, it is plentiful on Mars.

Chapter 8: Light Assembly Required: Discovering Photosynthesis

- 141 “Food is simply sunlight”: Kellogg, *The New Dietetics: What to Eat and How*, 29.
- 142 to bolster the fortunes of his father: Beale and Beale, *Echoes of Ingen Housz: The Long Lost Story of the Genius Who Rescued the Habsburgs from Smallpox and Became the Father of Photosynthesis*, 29.
- 143 She was desperate to save: Van Klooster, “Jan Ingenhousz,” 353.

Notes

- 143 clergymen railed against the thought: Magiels, *From Sunlight to Insight*, 87.
143 “I feared I should remain”: Quoted in Beale and Beale, *Echoes*, 322.
143 some London doctors did: Beaudreau and Finger, “Medical Electricity and Madness in the 18th Century,” 338.
144 attempts by Swiss chemist Carl Scheele to replicate: Beale and Beale, *Echoes*, 270–71.
145 “secret operations of plants”: Quoted in Beale and Beale, *Echoes*, 279.
146 “When two dogs fight for a bone”: Quoted in Beale and Beale, *Echoes*, 323.
146 Nonetheless, Priestley promised: Magiels, “Dr. Jan IngenHousz, or Why Don’t We Know Who Discovered Photosynthesis?” 14.
146 he found no acknowledgment: Magiels, *From Sunlight*, 109.
146 “a sultan who did not tolerate”: Quoted in Magiels, *From Sunlight*, 109.
146 “If you have really publish’d this doctrine before me”: Quoted in Magiels, *From Sunlight*, 238–39.
146 in the appendix: Gest, “A ‘Misplaced Chapter’ in the History of Photosynthesis Research: The Second Publication (1796) on Plant Processes by Dr. Jan Ingen-Housz, MD, Discoverer of Photosynthesis,” 65.
147 “seeking truth, and knowledge”: Debus, *Chemistry and Medical Debate: Van Helmont to Boerhaave*, 33.
147 studied alchemy and magic: Hedesan, “The Influence of Louvain Teaching on Jan Baptist Van Helmont’s Adoption of Paracelsianism and Alchemy,” 240.
148 Nor did he endear himself: Rosenfeld, “The Last Alchemist—the First Biochemist: J. B. van Helmont (1577–1644),” 1756.
148 “Put a pair of sweaty underwear”: Quoted in Cockell, *The Equations of Life: How Physics Shapes Evolution*, 240.
148 “monstrous pamphlet”: Quoted in Pagel, *Joan Baptista van Helmont*, 12.
148 soil had lost just 2 ounces: Pagel, *Joan Baptista van Helmont*, 53.
148 not from water: Ingenhousz, *An Essay on the Food of Plants and the Renovation of Soils*, 2.
150 “Be a chemist and make millions”: Kamen, *Radiant Science, Dark Politics: A Memoir of the Nuclear Age*, 21.
150 on his fourth version: Yarris, “Ernest Lawrence’s Cyclotron: Invention for the Ages.”
151 coached by Jack Dempsey: Johnston, *A Bridge Not Attacked: Chemical Warfare Civilian Research During World War II*, 90.
151 “outspoken, abrasive”: Kamen, “Onward into a Fabulous Half-Century,” 139.
152 “During a recital of these troubles”: Kamen, *Radiant Science*, 84.
153 shouldn’t take more than a few months: Kamen, “A Cupful of Luck, a Pinch of Sagacity,” 6.
153 proton-neutron pairs: Larson, interview with Martin Kamen, *Pioneers in Science and Technology Series, Center for Oak Ridge Oral History*, 11.

Notes

- 153 “three mad men hopping about”: Kamen, *Radiant Science*, 86.
154 Robert Oppenheimer told him: Kamen, “Early History of Carbon-14,” 586.
155 began firing alpha particles: Kamen, “Early History,” 588.
157 50 percent of its mass is carbon, and 44 percent is oxygen: Petterson, “The Chemical Composition of Wood,” 58.
157 About 83 percent: Russell and Williams, *The Nutrition and Health Dictionary*, 137.
158 fell asleep at the wheel: Kamen, *Radiant Science*, 165.
158 perhaps he was too impatient: Benson, “Following the Path of Carbon in Photosynthesis,” 35.
159 might leak atom bomb secrets: Larson, interview with Martin Kamen.
159 which were both trailing him: Kelly, “John Earl Haynes’s Interview.”
160 he chose to sit at the physicists’ table: Calvin, *Following the Trail of Light: A Scientific Odyssey*, 51.
160 “Time to quit”: Hargittai and Hargittai, *Candid Science V*, 386.
160 unlimited artificial food: Alsop, “Political Impact Is Seen in New Atomic Experiments.”
160 solve the world’s energy problem: Hargittai and Hargittai, *Candid Science V*, 388.
161 Benson realized: Buchanan and Wong, “A Conversation with Andrew Benson: Reflections on the Discovery of the Calvin–Benson Cycle,” 210.
161 “What’s new?”: Buchanan and Wong, “A Conversation,” 213.
161 “He would come tearing into the lab”: Moses and Moses, “Interview with Rod Quayle,” 6.
162 “He could make interpretations”: Moses and Moses, “Interview with Al Bassham,” 14.
162 jumped to his feet: Benson, “Following,” 809.
163 while Benson didn’t bother telling him: Sharkey, “Discovery of the Canonical Calvin–Benson Cycle,” 242.
163 “Time to go”: Buchanan and Wong, “A Conversation,” 213.
164 with a kick of energy from another light beam: Research into the “light reactions” has also been the subject of tremendous amount of research. Govindjee, Shevela, and Björn, “Evolution of the Z–Scheme of Photosynthesis.”
164 to simulate the process in a computer: Author interview with Stephen Long, University of Illinois Urbana-Champaign, November 2021.
164 a hundred times more slowly: Falkowski, *Life’s Engines: How Microbes Made Earth Habitable*, 99.
164 “Rubisco is a silly enzyme”: Author interview with Govindjee, University of Illinois Urbana-Champaign, May 2019.
165 700 million tons: Bar-On and Milo, “The Global Mass and Average Rate of Rubisco,” 4738.
165 artificial photosynthetic device: Calvin, “Photosynthesis as a Resource for Energy and Materials,” 277.

Notes

- 165 Researchers are still pursuing: Bourzac, “To Feed the World, Improve Photosynthesis.”
- 165 “region of transformation of cosmic energy”: Vernadsky, *The Biosphere*, 47.

Chapter 9: Lucky Breaks: From Ocean Scum to Green Planet

- 167 “Today photosynthesis runs our planet”: Author interview with Stjepko Golubic, July 2019.
- 168 as extreme as a nuclear holocaust: Margulis and Sagan, *Microcosmos: Four Billion Years of Evolution from Our Microbial Ancestors*, 109.
- 168 No one had found any evidence: The geologist John Dawson thought he had found an older fossil called *Eozoön*, but his claim did not hold up. Schopf, *Cradle of Life: The Discovery of Earth’s Earliest Fossils*, 19–21.
- 168 “driving frozen mist”: Walcott, “Pre-Carboniferous Strata in the Grand Canyon of the Colorado, Arizona,” 438.
- 168 food to last three months: Walcott, “Report of Mr. Charles D. Walcott, July 2,” 160.
- 168 “So much snow”: Schuchert, “Charles Doolittle Walcott, (1850–1927),” 279.
- 169 “rocks-rocks-rocks”: Yochelson, *Charles Doolittle Walcott, Paleontologist*, 145.
- 169 were forced to pile ice: Walcott, “Report of Mr. Charles D. Walcott, July 2,” 47.
- 169 created by some kind of life: Walcott, *Pre-Cambrian Fossiliferous Formations*, 234.
- 170 Other paleontologists also found unusual patterns: Schopf, *Life in Deep Time: Darwin’s “Missing” Fossil Record*, 49.
- 170 one long-disputed fossil: Schopf, *Cradle of Life*, 19–21. The fossil was called *Eozoön*.
- 170 As the paleobiologist William Schopf put it: Schopf, *Cradle of Life*, 31.
- 170 calcium-rich mud: Seward, *Plant Life through the Ages: A Geological and Botanical Retrospect*, 87.
- 170 we could never expect creatures as small as bacteria: Seward, *Plant Life*, 92.
- 170 many scientists used the term: Author interview with Stjepko Golubic, July 2019.
- 171 it dawned on them: Although earlier researchers working elsewhere, particularly in the Bahamas, had previously made the connection between cyanobacteria and ancient stromatolites, their claims were not widely accepted. The “living” stromatolites they pointed to looked very different from ancient *Cryptozoön*. In contrast, Logan’s stromatolites had an obvious resemblance to the ancient fossils. Hoffman, “Recent and Ancient Algal Stromatolites,” 180–81.
- 171 The mats trapped sediments: Prothero, *The Story of Life in 25 Fossils: Tales of Intrepid Fossil Hunters and the Wonders of Evolution*, 11.
- 172 They were microbial Bolsheviks: Falkowski, *Life’s Engines: How Microbes Made Earth Habitable*, 72.

Notes

- 172 desk and chair on four-inch risers: Author interview with William Schopf, UCLA, July 2019.
- 172 bantam-weight boxing champion: Crowell, "Preston Cloud," 45.
- 173 They kept it a secret: Author interview with William Schopf, UCLA, July 2019.
- 174 "Many kinds of microbes were immediately wiped out": Margulis and Sagan, *Microcosmos*, 108.
- 177 Budyko had even created a model: Walker, *Snowball Earth: The Story of the Great Global Catastrophe That Spawned Life as We Know It*, 113.
- 179 could have possibly formed: Walker, *Snowball Earth*, 122–28.
- 180 "we would never have come out of the snowball": Kirschvink believes that if the Earth had been slightly more distant from the Sun, the temperatures at Earth's poles would have been so frigid that the insulating carbon dioxide gas vented by volcanoes would have frozen when it reached the poles. The planet would have been too cold to ever escape Snowball Earth. This suggests to Kirschvink that there may be many other Earthlike planets where life evolved and then completely froze over.
- 181 quick-tempered: *The Telegraph*, "Lynn Margulis."
- 181 "Lynn was good as a needler": Author interview with Fred Spiegel, University of Arkansas, March 2019.
- 182 "She liked to start trouble": Dorion Sagan interview in *Symbiotic Earth*.
- 182 without bothering to tell her parents: Margulis, "Mixing It Up," 103–4.
- 182 "big shot": Quoted in Goldscheider, "Evolution Revolution," 46.
- 182 statement by one of her professors: Quammen, *The Tangled Tree: A Radical New History of Life*, 120.
- 182 Despite her thesis advisor's skepticism: Quammen, *The Tangled Tree*, 120.
- 182 like looking for Father Christmas: Poundstone, *Carl Sagan: A Life in the Cosmos*, 63.
- 183 as Margulis sat reading: Otis, *Rethinking Thought: Inside the Minds of Creative Scientists and Artists*, 36.
- 183 hit her like lightning: Otis, *Rethinking Thought*, 19.
- 183 "never changed a diaper in his life": Quoted in Davidson, *Carl Sagan: A Life*, 112.
- 184 "a torture chamber": Quoted in Poundstone, *Carl Sagan: A Life in the Cosmos*, 47.
- 184 two scientists in Sweden: Sagan, *Lynn Margulis: The Life and Legacy of a Scientific Rebel*, 59.
- 185 "Your research is crap": *The Telegraph*, "Lynn Margulis."
- 185 "it avoids the difficult thought": Sapp, *Evolution by Association*, 185.
- 186 "the greatest chemical inventors": Margulis and Sagan, *What Is Life?* 52.
- 187 "It may come as a blow": Quoted in Goldscheider, "Evolution Revolution," 44.
- 187 "As her career progressed": Author interview with John Archibald, Dalhousie University, March 2019.

Notes

- 187 by 1.7 billion years ago, if not earlier: Knoll, *A Brief History of Earth: Four Billion Years in Eight Chapters*, 108–11.
- 188 may have had three thousand of them: Author interview with Nick Lane, University College London, September 2019.
- 188 without a lot of overhead: Lane and Martin argue that there is a net energy savings. A mitochondrion living inside another cell no longer has to duplicate some jobs like building a cell wall. Overall, a mitochondrion and its host have to perform less work than if they lived separately.
- 188 about a quadrillion: Lane, “Why Is Life the Way It Is?” 23.
- 188 It will look like microorganisms: Lane, “Why Is Life the Way It Is?” 27; and Catling et al., “Why O₂ Is Required by Complex Life on Habitable Planets and the Concept of Planetary ‘Oxygenation Time.’”
- 188 by about 1.25 billion years ago: Gibson et al., “Precise Age of *Bangiomorpha pubescens* Dates the Origin of Eukaryotic Photosynthesis.” The oldest fossils found so far date to 1.047 billion years, but molecular clock evidence suggests that their ancestors appeared at least 1.25 billion years ago.
- 189 large fast-moving animals in the oceans didn’t show up: There were strange, slow-moving animals during the earlier Ediacaran period that began about 635 million years ago.
- 189 less than 1 percent oxygen: Falkowski, *Life’s Engines*, 130.
- 190 until 800 million years ago: Reinhard et al., “Evolution of the Global Phosphorus Cycle,” 386.
- 192 30 percent of our protein is collagen: Milo and Phillips, *Cell Biology by the Numbers*, 111.
- 193 to a staggering 30 to 35 percent: Falkowski, *Life’s Engines*, 141.
- 193 thirty-six thousand gallons: Kahn, “How Much Oxygen Does a Person Consume in a Day?”

Chapter 10: Planting the Seeds: How Greenery and Its Allies Made Us Possible

- 195 “Shall I not have intelligence”: Thoreau, *Walden*, 130.
- 195 from fiercely defending: Zimmermann, “Nachrufe: Simon Schwendener,” 59.
- 196 a tenth of 1 percent: Bar-On, Phillips, and Milo, “The Biomass Distribution on Earth.”
- 196 kept him from marrying: Honegger, “Simon Schwendener (1829–1919) and the Dual Hypothesis of Lichens,” 312.
- 196 “master is a fungus”: Plitt, “A Short History of Lichenology,” 89.
- 197 “Destructiveness is a character of fungi”: Ralfs, “The Lichens of West Cornwall,” 211.
- 197 “an assertion either of pure fantasy”: Plitt, “A Short History,” 82.
- 197 “Romance of Lichenology”: James Crombie, quoted in Smith, *Lichens*, xxv.
- 197 “met with the ridicule it deserved”: Step, *Plant-Life*, 149.
- 197 still dismissed Schwendener’s claim: Schmidt, “Essai d’une biologie de l’holophyte des Lichens,” 7.

Notes

- 199 preventing the ends of the roots: Ryan, *Darwin's Blind Spot*, 22.
- 199 on trees both young and old: Frank, "On the Nutritional Dependence of Certain Trees on Root Symbiosis with Belowground Fungi (an English Translation of A. B. Frank's Classic Paper of 1885)," 271.
- 199 Frank coined the word: A year after Frank coined *symbiotismus*, the botanist Anton de Bary introduced the term *symbiosis*, meaning "the living together of unlike organisms."
- 199 "wet nurse": Frank, "On the Nutritional Dependence," 274.
- 199 "calculated to try our patience": Ryan, *Darwin's Blind Spot*, 49.
- 199 structures that look just like mycorrhizal fungi: Beerling, *Making Eden*, 125–26.
- 200 "revolutionary announcement": "Hermann Hellriegel," 11.
- 200 "Their children suffered": Aulie, "Boussingault and the Nitrogen Cycle," doctoral thesis, 39.
- 201 "we passed from class to class": Mccosh, *Boussingault*, 4.
- 202 In one impressive trial: Aulie, "Boussingault and the Nitrogen Cycle," 448.
- 202 increased its nitrogen content by a third: Aulie, "Boussingault and the Nitrogen Cycle," 447.
- 203 if something in the soil was helping plants: Nutman, "Centenary Lecture," 72.
- 203 Cries of "bravo!": Finlay, "Science, Promotion, and Scandal," 209.
- 203 "highly gifted": MacFarlane, "The Transmutation of Nitrogen," 49.
- 204 almost 50 percent smaller: Erisman et al., "How a Century of Ammonia Synthesis Changed the World," 637.
- 205 Lignin is the second most abundant: Walker, *Plants: A Very Short Introduction*, 30.
- 205 fourteen billion of them: Datta et al., "Root Hairs," 1.
- 205 "They suck up all the nutrients": Author interview with Simon Gilroy, University of Wisconsin–Madison, November 2021.
- 206 more than 1,150 prairie plants: Tobey, *Saving the Prairies: The Life Cycle of the Founding School of American Plant Ecology, 1895–1955*, 192–93.
- 206 burrowed thirty-one feet down: Wilson, *Roots: Miracles Below*, 84.
- 207 "Why do plants make cocaine?": Author interview with Tony Trewavas, University of Edinburgh, September 2019.
- 207 at least 100,000 genes: Wade, "Number of Human Genes Is Put at 140,000, a Significant Gain."
- 207 About a third of your genes: Author interview with the scientist who made this finding: Lawrence Brody, National Institutes of Health, September 2021.
- 209 "Well, *we* could actually": Author interview with Jack Schultz, University of Toledo, September 2019.
- 210 "It seemed too woo-woo": Author interview with Elizabeth Van Volkenburgh, University of Washington, September 2019.

Notes

- 213 “What long-term scientific benefits”: Alpi et al., “Plant Neurobiology: No Brain, No Gain?” 136.
- 214 plants have over fifteen senses: Mancuso and Viola, *Brilliant Green: The Surprising History and Science of Plant Intelligence*, 77.
- 214 They detect neighboring plants with photoreceptors: Trewavas, “Mindless Mastery,” 841.
- 214 “If you grow plants”: Author interview with Janet Braam, Rice University, September 2019.
- 215 can end up high in a neighboring spruce: Yong, “Trees Have Their Own Internet.”
- 215 which should receive: Trewavas, “The Foundations of Plant Intelligence,” 11.
- 215 “explosive growth”: Trewavas, “Mindless Mastery,” 841.
- 216 “purpose driven”: Trewavas and Baluška, “The Ubiquity of Consciousness,” 1225.
- 216 “we should be aware”: Baluška and Mancuso, “Deep Evolutionary Origins of Neurobiology,” 63.
- 217 Simply covering our skin with chloroplasts: Milo and Phillips, *Cell Biology by the Numbers*, 169.

Chapter 11: So Much Depends on So Little: What Do You Need to Eat to Survive?

- 221 “Imagine all the food”: Tegmark, “Solid. Liquid. Consciousness.”
- 221 “fiery and impetuous”: Thorpe, *Essays in Historical Chemistry*, 316.
- 222 “built up new kingdoms”: Hofmann, *The Life-Work of Liebig*, 17.
- 222 *schafskopf*: Brock, *Justus Von Liebig: The Chemical Gatekeeper*, 6.
- 223 Gay-Lussac insisted that they dance: Brock, *Justus Von Liebig*, 32.
- 223 “provincial backwater”: Brock, *Justus Von Liebig*, 38.
- 223 “rules useful for making soda and soap”: Turner, “Justus Liebig versus Prussian Chemistry,” 131.
- 223 “The consciousness dawned on me”: Liebig, “Justus Von Liebig: An Autobiographical Sketch,” 661.
- 223 fume hoods: Morris, *The Matter Factory: A History of the Chemistry Laboratory*, 93.
- 224 “Storming and raging”: Mulder, *Liebig’s Question to Mulder Tested by Morality and Science*, 6.
- 224 “has arisen out of a complete ignorance”: Phillips, “Liebig and Kolbe, Critical Editors,” 91.
- 225 “In living Nature”: Hunter, *Vital Forces*, 56.
- 225 “the principles of chemistry and vitality”: Klickstein, “Charles Caldwell and the Controversy in America over Liebig’s ‘Animal Chemistry,’” 141.
- 226 feces of boa constrictors: Brucer, “Nuclear Medicine Begins with a Boa Constrictor,” 280.
- 226 about six tablespoons a day: We produce roughly eight cups of gastric juice that is about 5 percent hydrochloric acid.

Notes

- 226 God would not have put them there: Carpenter, *Protein and Energy: A Study of Changing Ideas in Nutrition*, 59.
- 226 “Vegetables produce in their organism”: Liebig, *Animal Chemistry: Or Organic Chemistry in Its Application to Physiology and Pathology*, 48.
- 226 failed to find carbohydrates or fats: Carpenter, *Protein and Energy*, 48.
- 227 “According to Liebig”: Thoreau, *Walden*, 11.
- 227 they needed to drink beer: Bissonnette, *It’s All about Nutrition*, 45.
- 227 “experienced the highest admiration”: Liebig, *Animal Chemistry*, vi.
- 227 “filled me with admiration”: Bence-Jones, Henry Bence-Jones, M.D., F.R.S. 1813–1873: *Autobiography with Elucidations at Later Dates*, 16.
- 227 “living scientific pioneer”: Morris, *The Matter Factory*, 30.
- 228 it occurred to the Swiss scientists: Carpenter, Harper, and Olson, “Experiments That Changed Nutritional Thinking,” 1120S–1121S.
- 228 faithfully collected their urine: Carpenter, Harper, and Olson, “Experiments,” 1021.
- 228 that turned out to be equally damaging: Carpenter, *Protein and Energy*, 71–72.
- 229 with convoluted arguments: Carpenter, “A Short History of Nutritional Science: Part 1 (1785–1885),” 642.
- 230 “the most perfect substitute”: Apple, “Science Gendered: Nutrition in the United States 1840–1940,” 133.
- 230 babies raised solely on his formula did not thrive: Carpenter, *Protein and Energy*, 74.
- 230 scurvy killed about two million sailors: Carpenter, *The History of Scurvy and Vitamin C*, 253.
- 231 he needed thirty-two wagons: Bown, *Scurvy: How a Surgeon, a Mariner, and a Gentlemen Solved the Greatest Medical Mystery of the Age of Sail*, 68.
- 231 about 400 of his 1,900 men: Frankenburg, *Vitamin Discoveries and Disasters*, 72.
- 231 captains made mad dashes from port to port: Bown, *Scurvy*, 75.
- 231 recommended lemon juice daily: Roddis, James Lind, *Founder of Nautical Medicine*, 55.
- 232 Over time, unfortunately, the knowledge: Bown, *Scurvy*, 74.
- 232 there were even “anti-fruiterers”: Harvie, *Limeys*, 56.
- 232 Lind had seen relatively little scurvy: Lind, *A Treatise on the Scurvy, in Three Parts: Containing an Inquiry into the Nature, Causes, and Cure of That Disease, Together with a Critical and Chronological View of What Has Been Published on the Subject*, 72.
- 232 “They had been afflicted by scurvy”: Lind, *A Treatise*, 62–63.
- 232 only sluggish and lazy sailors succumbed: Gratzner, *Terrors of the Table*, 17.
- 232 it simply seemed more expedient: Harvie, *Limeys*, 18.
- 234 “If there was ever a researcher”: Frankenburg, *Vitamin*, 78.
- 234 “Dr. Lind reckons the want”: Meiklejohn, “The Curious Obscurity of Dr. James Lind,” 307.

Notes

- 234 Another 133,708 expired: Bown, *Scurvy*, 26.
- 235 afflicted 7 percent: Braddon, *The Cause and Prevention of Beri-Beri*, 248.
- 236 at the elegant Café Bauer: Beek, *Dutch Pioneers of Science*, 138.
- 236 “legs and feet perfectly numbed”: Carpenter, *Beriberi, White Rice, and Vitamin B: A Disease, a Cause, and a Cure*, 27.
- 236 tantamount to a death sentence: Eijkman, “Christiaan Eijkman Nobel Lecture, 1929.”
- 237 the physicians recommended sterilizing: Carpenter, *Beriberi*, 35.
- 237 10 miles an hour: “Tracing the Lost Railway Lines of Indonesia.”
- 237 seemed more appetizing: Carpenter, *Beriberi*, 41.
- 237 they were cheaper to keep: Carpenter, *Beriberi*, 198.
- 238 “his successor refused to allow”: Eijkman, “Christiaan Eijkman Nobel Lecture, 1929.”
- 238 “chance favors only”: Houston, *A Treasury of the World’s Great Speeches*, 470.
- 238 a flurry of experiments: Carpenter, *Beriberi*, 40–41.
- 239 when bacteria in our stomachs feed on white rice: Carpenter, *Beriberi*, 45.
- 239 “as eating fish had to do with leprosy”: Vedder, *Beriberi*, 160.
- 239 prompted a British physician: Gratzer, *Terrors of the Table*, 141–42.
- 240 “So much careful scientific work”: Hopkins, *Newer Aspects of the Nutrition Problem*, 15.
- 240 Working alone at “full blast”: Maltz, “Casimer Funk, Nonconformist Nomenclature, and Networks Surrounding the Discovery of Vitamins,” 1016.
- 241 still questioned the validity of his “cure”: Maltz, “Casimer Funk,” 1016.
- 242 “a vitamin is a substance”: Quoted in Gratzer, *Terrors of the Table*, 162.
- 243 “Scientists Find Indication”: *New York Times*, “Scientists Find Indication of a Vitamin Which Prevents Softening of the Brain.”
- 243 and prevent cancer: *St. Louis Post-Dispatch*, “Is Vitamine Starvation the True Cause of Cancer?”
- 243 vitamin-deficient troops: Price, *Vitamania: How Vitamins Revolutionized the Way We Think about Food*, 75–78.
- 243 “You’re in the Army, too!”: Quoted in Bobrow-Strain, *White Bread: A Social History of the Store-Bought Loaf*, 119.
- 244 “Vitamins are another name”: BBC radio, “Enzymes,” *In Our Time*.
- 244 around 60 million years ago: Zimmer, “Vitamins’ Old, Old Edge.”
- 245 Harold White suspects: Zimmer, “Vitamins’ Old, Old Edge.”
- 246 nylon, acetone, formaldehyde, and coal tar: Price, *Vitamania*, 17.
- 247 “the most expensive urine”: Author interview with Gerald Combs Jr., Tufts University November 2019.
- 247 Beginning in the 1930s: Carpenter, “A Short History of Nutritional Science: Part 3 (1912–1944),” 3030.
- 248 arsenic: Collins, *Molecular, Genetic, and Nutritional Aspects of Major and Trace Minerals*, 528.

Notes

- 248 “Anything that’s in the soil”: Author interview with James F. Collins, University of Florida, February 2020.
- 249 mineral and vitamin deficiencies: Lieberman, *The Story of the Human Body: Evolution, Health, and Disease*, 191.
- 249 a handful from bacteria: Some bacteria in our guts make vitamins for us, including B vitamins and vitamin K.

Chapter 12: Hidden in Plain Sight: The Discovery of Your Master Blueprint

- 250 “Exploratory research”: Horgan, “Francis H. C. Crick: The Mephistopheles of Neurobiology,” 33.
- 251 thirty-some years after: Miescher came close to making this prediction in 1892.
- 251 among the simplest cells of all: Dahm, “Discovering DNA,” 576.
- 251 “cloudy, thick, slimy mass”: Olby, “Cell Chemistry in Miescher’s Day,” 379.
- 251 something never done before: Dahm, “The First Discovery of DNA,” 321.
- 252 On his wedding day: Meuron-Landolt, “Johannes Friedrich Miescher: sa personnalité et l’importance de son œuvre,” 20.
- 253 “If one . . . wants to assume”: Dahm, “Friedrich Miescher and the Discovery of DNA,” 282.
- 253 in a remarkable letter to his uncle: Lamm, Harman, and Veigl, “Before Watson and Crick in 1953 Came Friedrich Miescher in 1869,” 294–95.
- 253 Overwork weakened his immune system: Dahm, “The First,” 327.
- 253 it was nuclein, not protein: Mirsky, “The Discovery of DNA,” 86–88.
- 255 killed fifty thousand Americans: Perutz, “Co-Chairman’s Remarks: Before the Double Helix,” 10.
- 255 would sit for days mulling: MacLeod, “Obituary Notice, Oswald Theodore Avery, 1877–1955,” 544.
- 255 “focused inwardly as if unconcerned”: Dubos, “Oswald Theodore Avery, 1877–1955,” 35.
- 256 would not let his associates: Williams, *Unravelling the Double Helix: The Lost Heroes of DNA*, 148–49.
- 256 while Avery was away on vacation: Dubos, “Rene Dubos’s Memories of Working in Oswald Avery’s Laboratory.”
- 256 Dr. Jekylls into Mr. Hydes: Dubos, *The Professor, the Institute, and DNA*, 116.
- 256 something from the deceased lethal bacteria: McCarty, *The Transforming Principle: Discovering That Genes Are Made of DNA*, 92.
- 256 just over a hundred pounds: McCarty, *The Transforming Principle*, 87.
- 256 “headaches and heartbreaks”: In a letter to his brother Roy: Dubos, *The Professor*, 217.
- 256 “Disappointment is my daily bread”: Dubos, *The Professor*, 139.
- 257 treated the extract with enzymes: Letter from Avery to his brother, in Dubos, *The Professor*, 219.

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- 257 skepticism and sarcasm: Dubos, *The Professor*, 106.
- 257 “What else do you want, Fess?”: McCarty, *The Transforming Principle*, 163.
- 258 “has long been the dream of geneticists”: Dubos, *The Professor*, 245.
- 258 just a tenth of a percent of protein: McCarty, *The Transforming Principle*, 173.
- 258 “some goddamn other macromolecule”: Judson, *The Eighth Day of Creation: Makers of the Revolution in Biology*, 60.
- 258 “I saw before me”: Chargaff, *Heraclitean Fire: Sketches from a Life Before Nature*, 83.
- 259 in an ox’s DNA, the ratios of the bases: Williams, *Unravelling*, 246.
- 261 he wrote to request: Wilkins, *Maurice Wilkins: The Third Man of the Double Helix: An Autobiography*, 143–50.
- 261 It was at this very same time: Wilkins, *Maurice Wilkins*, 129.
- 262 she knew much more about the tricky techniques: Maddox, *Rosalind Franklin: The Dark Lady of DNA*, 144–45.
- 262 Why did he keep trying to move in on her turf?: Maddox, *Rosalind Franklin*, 153–55.
- 262 “She was quite sharp and quick and decisive”: Cold Spring Harbor Laboratory, “Aaron Klug on Rosalind Franklin.”
- 263 “A certain youthful arrogance”: Crick, *What Mad Pursuit*, 64.
- 265 she saw no point: Maddox, *Rosalind Franklin*, 161.
- 265 “like a spy”: Watson interview in PBS documentary, Babcock and Eriksson, *DNA: The Secret of Life*.
- 266 “until the cows come home”: Quoted in Watson, Gann, and Witkowski, *The Annotated and Illustrated Double Helix*, 91.
- 268 “in male-chauvinist fashion”: Author interview with Don Caspar, May 2020.
- 268 “I was the only person in the world”: Web of Stories interview with Watson, “Complementarity and My Place in History.”
- 269 a sixty-two-hour exposure: Williams, *Unravelling*, 327.
- 270 she had asked Gosling: Wilkins, *Maurice Wilkins*, 198.
- 270 the density of the X-ray image suggested: Watson and Berry, *DNA: The Secret of Life*, 51.
- 271 he had seen a similar measurement: Olby, *The Path to the Double Helix*, 403.
- 272 “it was almost impossible”: Web of Stories interview with Crick, “Molecular Biology in the Late 1940s.”
- 272 although Crick didn’t boast about it publicly: Markel, *The Secret of Life*, 12.
- 272 “It seemed that nonliving atoms”: Wilkins, *Maurice Wilkins*, 212.
- 273 “We all stand on each other’s shoulders”: “Due Credit,” 270.
- 273 must be in some way “interchangeable”: Maddox, *Rosalind Franklin*, 202.
- 274 “It’s so beautiful, you see”: Crick, *What Mad Pursuit*, 79.
- 274 “Can you patent it?”: Watson and Berry, *DNA*, 58.
- 275 in a “confused phase”: Crick, “Biochemical Activities of Nucleic Acids: The Present Position of the Coding Problem,” 35.

Notes

- 279 Most degrade after a few hours or days: Milo and Phillips, *Cell Biology by the Numbers*, 248.
- 279 tens of thousands of copies: A cell contains about ten billion proteins, according to *Cell Biology by the Numbers*, and the average half-life of a protein is seven hours. That means every seven hours you replace half of your ten billion proteins or over thirty-nine thousand a second.
- 279 when genes turn on and off: The base sequences controlling when genes are expressed are known as transcription factor binding sites, activators, promoters, enhancers, repressors, silencers, and control elements.

Chapter 13: Elements and All: What Is Really Inside You?

- 281 “Man, like other organisms”: Claude, “The Coming of Age of the Cell,” 434.
- 281 thirty trillion units, or cells: Sender, Fuchs, and Milo, “Revised Estimates for the Number of Human and Bacteria Cells in the Body,” 9.
- 282 he was seized by the desire: Brachet, “Notice sur Albert Claude,” 95.
- 282 Risking his life: Gompel, *Le destin extraordinaire d’Albert Claude (1898–1983)*, 26.
- 282 despite fearing his classes would all be taught in Latin: de Duve and Palade, “Obituary: Albert Claude, 1899–1983,” 588.
- 282 “blurred boundary which concealed”: Claude, “The Coming,” 433.
- 283 as mockingly distant as stars: Claude, “The Coming,” 433.
- 283 “biochemical bog”: Moberg, *Entering an Unseen World: A Founding Laboratory and Origins of Modern Cell Biology, 1910–1974*, 137.
- 283 leave the premises as soon as possible: Brachet, “Notice,” 100.
- 284 like a solitary wild boar: Brachet, “Notice,” 118.
- 284 wanted to replace him with an actual chemist: Moberg, *Entering*, 23.
- 284 about 17,000 g: Claude, “Fractionation of Chicken Tumor Extracts by High Speed Centrifugation,” 743.
- 284 with a mortar and pestle: de Duve and Beaufay, “A Short History of Tissue Fractionation,” 24.
- 284 he determined that it contained RNA: de Duve and Palade, “Obituary,” 588.
- 285 take a hammer to cells: *Interview with Albert Claude*, Rockefeller Institute Archive Center, RAC FA1444 (Box 1, Folder 5).
- 285 “When he started tearing cells apart”: Moberg, *Entering*, 38.
- 285 “cellular mayonnaise”: Rheinberger, “Claude, Albert,” 146.
- 285 Some colleagues saw it as a betrayal: Brachet, “Notice,” 108.
- 285 “accident of technical progress”: Claude, “Albert Claude, 1948,” 121.
- 286 master in taking advantage of them: Rheinberger, “Claude, Albert,” 146.
- 286 chemical factories: Moberg, *Entering*, 76.
- 286 “would serve no useful purpose”: Hawkes, “Ernst Ruska,” 84.
- 287 it had killed one of his close friends: Moberg, *Entering*, 55.
- 287 “It was wonderful”: Moberg, *Entering*, 60.

Notes

- 288 His genius was apparently less in using his techniques: Palade, "Albert Claude and the Beginnings of Biological Electron Microscopy," 15–17.
- 289 "Many of his friends remember Mitchell": Prebble and Weber, *Wandering in the Gardens of the Mind*, 15.
- 289 the "power plants": Claude, "The Coming," 434.
- 290 ten to one hundred million ATPs: Flamholz, Phillips, and Milo, "The Quantified Cell," 3499.
- 290 Big labs and big scientists competed: Gilbert and Mulkay, *Opening Pandora's Box*, 26. This entire book examines how scientists discussed and reacted to Mitchell's theory.
- 290 became a burning issue: Harold, *To Make the World Intelligible*, 121.
- 290 "only shadows of moving parts": Racker, "Reconstitution, Mechanism of Action and Control of Ion Pumps," 787.
- 290 "anyone who was not thoroughly confused": Racker, "Reconstitution," 787.
- 291 Heraclitus: Prebble, "The Philosophical Origins of Mitchell's Chemiosmotic Concepts," 443.
- 291 He had no experimental evidence: Prebble, "Peter Mitchell and the Ox Phos Wars," 209.
- 291 "I remember thinking to myself": Orgel, "Are You Serious, Dr. Mitchell?" 17.
- 291 "These formulations sounded like": Racker, "Reconstitution," 787.
- 292 He presented his theory in obscure terms: Harold, *To Make the World Intelligible*, 49.
- 292 Revenue from his prize dairy cows: Lane, *Power, Sex, Suicide*, 102.
- 292 "went into one of my ears": Govindjee and Krogmann, "A List of Personal Perspectives with Selected Quotations, along with Lists of Tributes, Historical Notes, Nobel and Kettering Awards Related to Photosynthesis," 16.
- 292 hopped on one foot in anger: Prebble, "Peter Mitchell and the Ox Phos Wars," 210.
- 292 Mitchell marked the locations: Saier, "Peter Mitchell and the Life Force," chapter 8, page 10 of 14.
- 292 almost 100 million volts per foot: Lane, *The Vital Question: Why Is Life the Way It Is?* 73.
- 293 three hundred times a second: Milo and Phillips, *Cell Biology by the Numbers*, 357.
- 293 describes it as: Walker, *Fuel of Life*.
- 293 for his "bioimagination": Roskoski, "Wandering in the Gardens of the Mind," 64–65.
- 293 Mitchell used the prize money: Saier, "Peter Mitchell and the Life Force," chapter 9, page 2 of 8.
- 294 Mike Russell and William Martin believe: Lane, *Life Ascending*, 32–33.
- 294 a thousand to ten thousand mitochondria: Milo and Phillips, *Cell Biology*, 34.
- 294 35 percent of a heart muscle cell's volume: Hom and Sheu, "Morphological Dynamics of Mitochondria: A Special Emphasis on Cardiac Muscle Cells," 7.

Notes

- 294 tens of thousands of times more energy: Author interview with Nick Lane, University College London, December 2021.
- 294 two-thirds of a pint of oxygen: Flamholz, Phillips, and Milo, "The Quantified Cell," 3499.
- 295 about a third of your energy: Hoffmann, *Life's Ratchet: How Molecular Machines Extract Order from Chaos*, 212.
- 295 more than a million sodium ions a second: Ashcroft, *The Spark of Life: Electricity in the Human Body*, 42.
- 296 a million sodium-potassium pumps: Stevens, "The Neuron," 57.
- 296 350 feet a second: Ashcroft, *The Spark of Life*, 56.
- 296 a cool quadrillion or so minuscule sodium-potassium pumps: Each of our hundred billion nerve cells has about a million sodium-potassium pumps. Each of our several million cardiac muscle cells contains a few million pumps. These alone add up to quadrillions of sodium-potassium pumps. Our other cells possess them in lesser numbers.
- 296 hunter-gatherers got their salt from meat: Lieberman, *The Story of the Human Body: Evolution, Health, and Disease*, 283.
- 298 a molecular storm: Hoffmann, *Life's Ratchet*, 72.
- 298 two million times a second: E-mail to author from Kim Sharp, University of Pennsylvania.
- 298 collides with every protein: Milo and Phillips, *Cell Biology*, 220.
- 298 four billionths of an inch: E-mail from Kim Sharp, University of Pennsylvania.
- 298 20 miles per hour: Bray, *Cell Movements*, 4.
- 299 once every ten thousand times: Lane, *The Vital*, 12.
- 299 one in a million to ten million or so: Estimates of incorporating the wrong base in DNA vary from one in a million to one in ten million. Repair mechanisms that immediately follow along decrease the error rate to perhaps one in ten billion.
- 299 "Bored with yourself?": *Atlanta Constitution*, "Each of Us Is Charged with Busy Little Atoms."
- 299 Aebersold proudly told: "Paul C. Aebersold Interview," *Longines Chronoscope*.
- 300 98 percent of all our atoms every year: Stager, *Your Atomic Self*, 213.
- 300 every ten years: Kirsty Spalding and Jonas Frisén were the first to recognize this. Wade, "Your Body Is Younger Than You Think." See also Milo and Phillips, *Cell Biology by the Numbers*, 279. While a few types of cells are not replaced at all, you replace the vast preponderance within ten years.
- 300 330 billion cells a day: Sender and Milo, "The Distribution of Cellular Turnover in the Human Body," 45.
- 300 replaced every two to four days: Milo and Phillips, *Cell Biology*, 279.
- 300 replaced every 120 days: Milo and Phillips, *Cell Biology*, 279.
- 300 three and a half million new red blood cells every second: Sender and Milo, "The Distribution," 45.

Notes

- 300 once every ten years: Milo and Phillips, *Cell Biology*, 279.
301 eighty-six billion neurons: Herculano-Houzel, “The Human Brain in Numbers,” 7.
302 about 1 percent: You replace heart cells at a rate of about 1 percent a year until you are about fifty, at which point the rate declines. Wade, “Heart Muscle Renewed over Lifetime, Study Finds.”
302 “I doubt we will ever find a way of living much beyond 120”: Lane, *The Vital*, 278.
303 hundreds of millions to a billion ATPs a second: Milo and Phillips, *Cell Biology*, 201. Milo and Phillips estimate that a mammalian cell with a volume of $3,000\text{ }\mu\text{m}^3$ consumes on the order of one billion ATPs a second.
303 a parking lot with a foot or less: Hoffmann, *Life’s Ratchet*, 107.

Conclusion: What a Long Strange Trip It’s Been

- 305 “Science, truly understood”: Donnan, “The Mystery of Life,” 514.
306 than there are stars in the Milky Way: The number of cells in the human body is on the order of thirty trillion. Sender, Fuchs, and Milo, “Revised Estimates for the Number of Human and Bacteria Cells in the Body.” The number of stars in the Milky Way is estimated to be one hundred billion to four hundred billion.
307 In Gell-Mann’s wide rearview mirror: Horgan, “From My Archives: Quark Inventor Murray Gell-Mann Doubts Science Will Discover ‘Something Else.’”
310 “We are a way for the cosmos to know itself”: Carl Sagan in the television series *Cosmos*.

BIBLIOGRAPHY

- Adan, Ana. "Cognitive Performance and Dehydration." *Journal of the American College of Nutrition* 31, no. 2 (April 1, 2012).
- Aikman, Duncan. "Lemaitre Follows Two Paths to Truth." *New York Times*, February 19, 1933.
- Aitkenhead, Alan R., Graham Smith, and David J. Rowbotham. *Textbook of Anaesthesia*, 5th ed. London: Elsevier, 2007.
- Albert Einstein College of Medicine. "Built-In 'Self-Destruct Timer' Causes Ultimate Death of Messenger RNA in Cells." Press release, December 22, 2011.
- Alpi, Amedeo, Nikolaus Amrhein, et al. "Plant Neurobiology: No Brain, No Gain?" *Trends in Plant Science* 12, no. 4 (April 2007).
- Alsop, Stewart. "Political Impact Is Seen in New Atomic Experiments." *Toledo Blade*, January 6, 1949.
- Amos, Jonathan. "Beer Microbes Live 553 Days Outside ISS." BBC News, August 23, 2010, <https://www.bbc.com/news/science-environment-11039206>.
- Anderson, Carl D., and Richard J. Weiss. *The Discovery of Anti-Matter: The Autobiography of Carl David Anderson, the Youngest Man to Win the Nobel Prize*. Singapore: World Scientific, 1999.
- Apple, Rima. "Science Gendered: Nutrition in the United States 1840–1940," in *The Science and Culture of Nutrition, 1840–1940*, ed. Harmke Kamminga and Andrew Cunningham. Amsterdam: Rodopi, 1995.
- Ashcroft, Frances. *The Spark of Life: Electricity in the Human Body*. New York: Norton, 2012.
- Atlanta Constitution*, "Each of Us Is Charged with Busy Little Atoms, November 8, 1954.
- Aulie, Richard P. "Boussingault and the Nitrogen Cycle." Doctoral thesis, Yale University, 1969.
- . "Boussingault and the Nitrogen Cycle." *Proceedings of the American Philosophical Society* 114, no. 6 (December 18, 1970).
- Babcock, Viki, and Magdalena Eriksson, writers; Ian Duncan and David Glover, directors. *DNA: The Secret of Life*, episode 1. Arlington, VA: Public Broadcasting Service, 2003.
- Bada, Jeffrey, and Antonio Lazcano. "Biographical Memoirs: Stanley L. Miller: 1930–2007." National Academy of Sciences, 2012, <http://www.nasonline.org/publications/biographical-memoirs/memoir-pdfs/miller-stanley.pdf>.
- Ballard, Robert D. *The Eternal Darkness: A Personal History of Deep-Sea Exploration*. Princeton, NJ: Princeton University Press, 2000.

Bibliography

- Baluška, František, and Stefano Mancuso. "Deep Evolutionary Origins of Neurobiology: Turning the Essence of 'Neural' Upside-Down." *Communicative & Integrative Biology* 2, no. 1 (December 1, 2009).
- Bangham, Alec D. "Surrogate Cells or Trojan Horses: The Discovery of Liposomes." *BioEssays* 17, no. 12 (1995).
- Barnes, E. W. "Contributions to a British Association Discussion on the Evolution of the Universe." *Nature*, no. 128 (October 24, 1931).
- Bar-On, Yinon M., and Ron Milo. "The Global Mass and Average Rate of Rubisco." *Proceedings of the National Academy of Sciences of the United States of America* 116, no. 10 (March 5, 2019).
- Bar-On, Yinon M., Rob Phillips, and Ron Milo. "The Biomass Distribution on Earth." *Proceedings of the National Academy of Sciences* 115, no. 25 (June 19, 2018).
- Barras, Colin. "Formation of Life's Building Blocks Recreated in Lab." *New Scientist*, no. 2999 (December 13, 2014).
- BBC documentary transcript. "Wilson of the Cloud Chamber," 1959.
- BBC *Horizon* documentary. "Life Is Impossible," 1993.
- BBC radio. "Enzymes." *In Our Time*, June 1, 2017.
- Beale, Norman, and Elaine Beale. *Echoes of Ingen Housz: The Long Lost Story of the Genius Who Rescued the Habsburgs from Smallpox and Became the Father of Photosynthesis*. Gloucester, UK: Hobnob Press, 2011.
- Beaudreau, Sherry Ann, and Stanley Finger. "Medical Electricity and Madness in the 18th Century: The Legacies of Benjamin Franklin and Jan Ingenhousz." *Perspectives in Biology and Medicine* 49, no. 3 (July 27, 2006).
- Beek, Leo. *Dutch Pioneers of Science*. Assen, Netherlands: Van Gorcum, 1985.
- Beerling, David. *Making Eden: How Plants Transformed a Barren Planet*. Oxford, UK: Oxford University Press, 2019.
- Bence-Jones, Henry. *Henry Bence-Jones, M.D., F.R.S. 1813–1873: Autobiography with Elucidations at Later Dates*. London: Crush & Son, 1929.
- Benson, Andrew A. "Following the Path of Carbon in Photosynthesis: A Personal Story." *Photosynthesis Research* 73, (July 1, 2002).
- Bernal, J. D. *The Origin of Life*. London: Weidenfeld & Nicolson, 1967.
- Bernstein, Jeremy. *A Palette of Particles*. Cambridge, MA: Harvard University Press, 2013.
- Bertolotti, Mario. *Celestial Messengers: Cosmic Rays: The Story of a Scientific Adventure*. Berlin: Springer, 2013.
- Bissonnette, David. *It's All about Nutrition: Saving the Health of Americans*. Lanham, MD: University Press of America, 2014.
- Blackmore, John T. *Ernst Mach: His Life, Work, and Influence*. Berkeley: University of California Press, 1972.
- Blatner, David. *Spectrums: Our Mind-Boggling Universe from Infinitesimal to Infinity*. London: Bloomsbury, 2013.
- Bobrow-Strain, Aaron. *White Bread: A Social History of the Store-Bought Loaf*. Boston: Beacon Press, 2012.

Bibliography

- Bourzac, Katherine. "To Feed the World, Improve Photosynthesis." *MIT Technology Review* 120, no. 5 (September 2017).
- Bown, Stephen R. *Scurvy: How a Surgeon, a Mariner, and a Gentleman Solved the Greatest Medical Mystery of the Age of Sail*. New York: St. Martin's Press, 2003.
- Brachet, Jean. "Notice sur Albert Claude." *Annuaire de l'Académie royale de Belgique*, 1988.
- Braddon, William Leonard. *The Cause and Prevention of Beri-Beri*. London: Rebman Limited, 1907.
- Bray, Dennis. *Cell Movements: From Molecules to Motility*. New York: Garland Science, 2001.
- Brock, William H. *Justus Von Liebig: The Chemical Gatekeeper*. Cambridge, UK: Cambridge University Press, 2002.
- Brownlee, Donald E. "Cosmic Dust: Building Blocks of Planets Falling from the Sky." *Elements* 12, no. 3 (June 1, 2016).
- Brucer, Marshall. "Nuclear Medicine Begins with a Boa Constrictor." *Journal of Nuclear Medicine Technology* 24, no. 4 (1996).
- Buchanan, Bob B., and Joshua H. Wong. "A Conversation with Andrew Benson: Reflections on the Discovery of the Calvin–Benson Cycle." *Photosynthesis Research* 114, no. 3 (March 1, 2013).
- Burbidge, Geoffrey. "Sir Fred Hoyle 24 June 1915–20 August 2001." *Biographical Memoirs of Fellows of the Royal Society* 49 (2003).
- Burns, Joseph A., Jack J. Lissauer, and Andrei Makalkin. "Victor Sergeyevich Saffronov (1917–1999)." *Icarus* 145, no. 1 (May 1, 2000).
- Butterworth, Jon. "How Big Is a Quark?" *The Guardian*, April 7, 2016, <https://www.theguardian.com/science/life-and-physics/2016/apr/07/how-big-is-a-quark>.
- Calder, Nigel. *Giotto to the Comets*. London: Presswork, 1992.
- California Institute of Technology. "Caltech Geologists Find New Evidence That Martian Meteorite Could Have Harbored Life," press release, March 13, 1997, <https://www2.jpl.nasa.gov/snc/news8.html>.
- Calvin, Melvin. *Following the Trail of Light: A Scientific Odyssey*. Washington, DC: American Chemical Society, 1992.
- . "Photosynthesis as a Resource for Energy and Materials: The Natural Photosynthetic Quantum-Capturing Mechanism of Some Plants May Provide a Design for a Synthetic System That Will Serve as a Renewable Resource for Material and Fuel." *American Scientist* 64, no. 3 (1976).
- Carpenter, Kenneth J. *Beriberi, White Rice, and Vitamin B: A Disease, a Cause, and a Cure*. Berkeley: University of California Press, 2000.
- . *The History of Scurvy and Vitamin C*. Cambridge, UK: Cambridge University Press, 1988.
- . *Protein and Energy: A Study of Changing Ideas in Nutrition*. Cambridge, UK: Cambridge University Press, 1994.
- . "A Short History of Nutritional Science: Part 1 (1785–1885)." *Journal of Nutrition* 133, no. 3 (March 2003).

Bibliography

- . “A Short History of Nutritional Science: Part 3 (1785–1885).” *Journal of Nutrition* 133, no. 10 (October 2003).
- Carpenter, Kenneth J., Alfred E. Harper, and Robert E. Olson. “Experiments That Changed Nutritional Thinking.” *Journal of Nutrition* 127, no. 5 (May 1997).
- Catling, David C., Christopher R. Glein, et al. “Why O₂ Is Required by Complex Life on Habitable Planets and the Concept of Planetary ‘Oxygenation Time.’” *Astrobiology* 5, no. 3 (June 2005).
- Chargaff, Erwin. *Heracleitean Fire: Sketches from a Life before Nature*. New York: Rockefeller University Press, 1978.
- Charitos, Panos. “Interview with George Zweig.” *CERN EP News*, December 13, 2013, <https://ep-news.web.cern.ch/content/interview-george-zweig>.
- Chu, Jennifer. “Physicists Calculate Proton’s Pressure Distribution for First Time.” *MIT News*, February 22, 2019, <https://news.mit.edu/2019/physicists-calculate-proton-pressure-distribution-0222>.
- Claude, Albert. “Albert Claude, 1948.” Harvey Society Lectures, Rockefeller University, January 1, 1950.
- . “The Coming of Age of the Cell.” *Science* 189, no. 4201 (August 8, 1975).
- . “Fractionation of Chicken Tumor Extracts by High Speed Centrifugation.” *American Journal of Cancer* 30, no. 4 (August 1, 1937).
- Close, Frank. *Particle Physics: A Very Short Introduction*. Oxford, UK: Oxford University Press, 2004.
- Close, Frank, Michael Marten, and Christine Sutton. *The Particle Odyssey: A Journey to the Heart of Matter*. Oxford, UK: Oxford University Press, 2004.
- Cockell, Charles S. *The Equations of Life: How Physics Shapes Evolution*. New York: Basic Books, 2018.
- Cold Spring Harbor Laboratory, Oral History Collection. “Aaron Klug on Rosalind Franklin,” June 17, 2005, <http://library.cshl.edu/oralhistory/interview/scientific-experience/women-science/aaron-rosalind-franklin/>.
- Collins, James F. *Molecular, Genetic, and Nutritional Aspects of Major and Trace Minerals*. San Diego: Academic Press, 2016.
- Compton, William. *Where No Man Has Gone Before: A History of Apollo Lunar Exploration Missions*. Washington, DC: NASA, 1988.
- Cooper, Geoffrey M., and Robert E. Hausman. *The Cell: A Molecular Approach*. Sunderland, MA: Sinauer Associates, 2013.
- Cooper, Henry S. F. *Apollo on the Moon*. New York: Dial Press, 1969.
- . “Letter from the Space Center.” *New Yorker*, July 25, 1969.
- Cooper, Keith. *Origins of the Universe: The Cosmic Microwave Background and the Search for Quantum Gravity*. London: Icon Books, 2020.
- Corfield, Richard. “One Giant Leap.” *Chemistry World*, August 2009.
- Cott, Jonathan. “The Cosmos: An Interview with Carl Sagan.” *Rolling Stone*, December 25, 1980.
- Cottrell, Geoff. *Matter: A Very Short Introduction*. Oxford, UK: Oxford University Press, 2019.

Bibliography

- Couper, Heather, and Nigel Henbest. *The History of Astronomy*. Richmond Hill, Ontario: Firefly Books, 2007.
- Cowan, Robert. "Scientists Uncover First Direct Evidence of Water in Halley's Comet: New Way to Study Comets Will Help Yield Clues to Solar System's Origin." *Christian Science Monitor*, January 13, 1986.
- Crane, Kathleen. *Sea Legs: Tales of a Woman Oceanographer*. Boulder, CO: Westview Press, 2003.
- Crease, Robert P., and Charles C. Mann. *The Second Creation: Makers of the Revolution in Twentieth-Century Physics*. New Brunswick, NJ: Rutgers University Press, 1996.
- Crick, Francis. "Biochemical Activities of Nucleic Acids: The Present Position of the Coding Problem." *Brookhaven Symposia in Biology* 12 (1959).
- . *What Mad Pursuit: A Personal View of Scientific Discovery*. New York: Basic Books, 1988.
- Crowell, John. "Preston Cloud," in *National Academy of Sciences: Biographical Memoirs*, vol. 67. Washington, DC: National Academy Press, 1995.
- Crowther, James. *Scientific Types*. Chester Springs, PA: Dufour, 1970.
- Dahm, Ralf. "Discovering DNA: Friedrich Miescher and the Early Years of Nucleic Acid Research." *Human Genetics* 122, no. 6 (January 2008).
- . "The First Discovery of DNA: Few Remember the Man Who Discovered the 'Molecule of Life' Three-Quarters of a Century before Watson and Crick Revealed Its Structure." *American Scientist* 96, no. 4 (2008).
- . "Friedrich Miescher and the Discovery of DNA." *Developmental Biology* 278, no. 2 (February 15, 2005).
- Datta, Sourav, Chul Min Kim, et al. "Root Hairs: Development, Growth and Evolution at the Plant-Soil Interface." *Plant and Soil* 346, no. 1 (September 1, 2011).
- Davidson, Keay. *Carl Sagan: A Life*. New York: Wiley, 1999.
- Deamer, David. *First Life: Discovering the Connections between Stars, Cells, and How Life Began*. Berkeley: University of California Press, 2012.
- Deamer, David W. "From 'Banghasomes' to Liposomes: A Memoir of Alec Bangham, 1921–2010." *FASEB Journal* 24, no. 5 (May 2010).
- de Angelis, Alessandro. "Atmospheric Ionization and Cosmic Rays: Studies and Measurements before 1912." *Astroparticle Physics* 53 (January 2014).
- Debus, Allen G. *Chemistry and Medical Debate: Van Helmont to Boerhaave*. Canton, MA: Science History, 2001.
- de Duve, Christian. "The Beginnings of Life on Earth." *American Scientist* 83, no. 5 (1995).
- de Duve, Christian, and Henri Beaufay. "A Short History of Tissue Fractionation." *Journal of Cell Biology* 91, no. 3 (December 1, 1981).
- de Duve, Christian, and George E. Palade. "Obituary: Albert Claude, 1899–1983." *Nature* 304, no. 5927 (August 18, 1983).
- Deprit, Andre. "Monsignor Georges Lemaître," in *The Big Bang and Georges Lemaître*:

Bibliography

- Proceedings of the Symposium, Louvain-La-Neuve, Belgium, October 10–13, 1983*, ed. A. Berger. Dordrecht, Netherlands: D. Reidel, 1984.
- de Maria, M., M. G. Ianniello, and A. Russo. “The Discovery of Cosmic Rays: Rivalries and Controversies between Europe and the United States.” *Historical Studies in the Physical and Biological Sciences* 22, no. 1 (1991).
- DeVorkin, David. AIP oral history interview with Bart Bok, May 17, 1978, <http://www.aip.org/history-programs/niels-bohr-library/oral-histories/4518-2>.
- . AIP oral history interview with Fred Whipple, April 29, 1977, <https://www.aip.org/history-programs/niels-bohr-library/oral-histories/5403>.
- DeVorkin, David H. *Henry Norris Russell: Dean of American Astronomers*. Princeton, NJ: Princeton University Press, 2000.
- Dick, Steven J., and James Edgar Strick. *The Living Universe: NASA and the Development of Astrobiology*. New Brunswick, NJ: Rutgers University Press, 2004.
- Donnan, Frederick G. “The Mystery of Life.” *Nature* 122, no. 3075 (October 1, 1928).
- Dubos, René Jules. “Oswald Theodore Avery, 1877–1955.” *Biographical Memoirs of Fellows of the Royal Society* 2 (November 1, 1956).
- . *The Professor, the Institute, and DNA*. New York: Rockefeller University Press, 1976.
- . “Rene Dubos’s Memories of Working in Oswald Avery’s Laboratory.” Symposium Celebrating the Thirty-Fifth Anniversary of the Publication of “Studies on the Chemical Nature of the Substance Inducing Transformation of Pneumococcal Types,” 1979, <https://profiles.nlm.nih.gov/101584575X343>.
- “Due Credit.” *Nature* 496, no. 7445 (April 18, 2013).
- Echols, Harrison G. *Operators and Promoters: The Story of Molecular Biology and Its Creators*. Berkeley: University of California Press, 2001.
- Eijkman, Christiaan. “Christiaan Eijkman Nobel Lecture, 1929,” NobelPrize.org.
- Eiseley, Loren C. *The Immense Journey*. New York: Vintage Books, 1957.
- Emsley, John. *Nature’s Building Blocks: An A–Z Guide to the Elements*. Oxford, UK: Oxford University Press, 2011.
- Erisman, Jan Willem, Mark A. Sutton, et al. “How a Century of Ammonia Synthesis Changed the World.” *Nature Geoscience* 1, no. 10 (October 2008).
- Eyles, Don. “Tales from the Lunar Module Guidance Computer.” Guidance and Control Conference of the American Astronautical Society, Breckenridge, CO, February 6, 2004.
- Falkowski, Paul G. *Life’s Engines: How Microbes Made Earth Habitable*. Princeton, NJ: Princeton University Press, 2016.
- Farrell, John. *The Day without Yesterday: Lemaitre, Einstein, and the Birth of Modern Cosmology*. New York: Basic Books, 2005.
- Finlay, Mark R. “Science, Promotion, and Scandal: Soil Bacteriology, Legume Inoculation, and the American Campaign for Soil Improvement in the Progressive Era,” in *New Perspectives on the History of Life Sciences and Agriculture*, ed. Denise Phillips and Sharon Kingsland. Heidelberg, Germany: Springer, 2015.

Bibliography

- Fisher, Arthur. "Birth of the Moon." *Popular Science* 230, no. 1 (January 1987).
- Flamholz, Avi, Rob Phillips, and Ron Milo. "The Quantified Cell." *Molecular Biology of the Cell* 25, no. 22 (November 5, 2014).
- Frank, A. B. "On the Nutritional Dependence of Certain Trees on Root Symbiosis with Belowground Fungi (an English Translation of A. B. Frank's Classic Paper of 1885)," trans. James Trappe. *Mycorrhiza* 15, no. 4 (June 2005).
- Frankenburg, Frances Rachel. *Vitamin Discoveries and Disasters: History, Science, and Controversies*. Santa Barbara: Prager, 2009.
- Frenkel, V., and A. Grib. "Einstein, Friedmann, Lemaître: Discovery of the Big Bang," in *Proceedings of the 2nd Alexander Friedmann International Seminar*. St. Petersburg, Russia: Friedmann Laboratory Publishing, 1994.
- Galison, Peter L. "Marietta Blau: Between Nazis and Nuclei." *Physics Today* 50, no. 11 (November 1997).
- Gbur, Greg. "Paris: City of Lights and Cosmic Rays." *Scientific American Blog*, July 4, 2011, <https://blogs.scientificamerican.com/guest-blog/paris-city-of-lights-and-cosmic-rays>.
- Gest, Howard. "A 'Misplaced Chapter' in the History of Photosynthesis Research: The Second Publication (1796) on Plant Processes by Dr. Jan Ingen-Housz, MD, Discoverer of Photosynthesis." *Photosynthesis Research* 53, no. 1 (July 1, 1997).
- Gibson, Timothy M., Patrick M. Shih, et al. "Precise Age of *Bangiomorpha pubescens* Dates the Origin of Eukaryotic Photosynthesis." *Geology* 46, no. 2 (February 2018).
- Gilbert, G. Nigel, and Michael Mulkay. *Opening Pandora's Box: A Sociological Analysis of Scientists' Discourse*. Cambridge, UK: Cambridge University Press, 1984.
- Gingerich, Owen. AIP oral history interview with Cecilia Payne-Gaposchkin, March 5, 1968, <https://www.aip.org/history-programs/niels-bohr-library/oral-histories/4620>.
- . "The Most Brilliant Ph.D. Thesis Ever Written in Astronomy," in *The Starry Universe: The Cecilia Payne-Gaposchkin Centenary: Proceedings of a Symposium Held at the Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts, October 26–27, 2000*. Schenectady, NY: L. Davis Press, 2001.
- Gitschier, Jane. "Meeting a Fork in the Road: An Interview with Tom Cech." *PLOS Genetics* 1, no. 6 (December 2005).
- Glashow, Sheldon. "Book Review of *Strange Beauty: Murray Gell-Mann and the Revolution in Twentieth-Century Physics*." *American Journal of Physics* 68, no. 6 (June 2000).
- Godart, O. "The Scientific Work of Georges Lemaître," in *The Big Bang and Georges Lemaître: Proceedings of a Symposium in Honour of G. Lemaître Fifty Years after His Initiation of Big-Bang Cosmology, Louvain-La-Neuve, Belgium, 10–13 October 1983*, ed. A. Berger. Heidelberg, Germany: Springer, 2012.
- Goldscheider, Eric. "Evolution Revolution." *On Wisconsin*, Fall 2009.
- Gompel, Claude. *Le destin extraordinaire d'Albert Claude (1898–1983): Découvreur de la cellule, Rénovateur de l'institut Bordet, Prix Nobel de Médecine 1974*. Île-de-France: Connaissances et Savoirs, 2012.

Bibliography

- Govindjee and David W. Krogmann. "A List of Personal Perspectives with Selected Quotations, along with Lists of Tributes, Historical Notes, Nobel and Kettering Awards Related to Photosynthesis." *Photosynthesis Research* 73, no. 1 (July 2002).
- Govindjee, Dmitriy Shevela, and Lars Olof Björn. "Evolution of the Z-Scheme of Photosynthesis: A Perspective." *Photosynthesis Research* 133, no. 1 (September 2017).
- Graham, Loren R. *Science in Russia and the Soviet Union: A Short History*. Cambridge, UK: Cambridge University Press, 1993.
- . *Science, Philosophy, and Human Behavior in the Soviet Union*. New York: Columbia University Press, 1987.
- Gratzler, Walter. *Terrors of the Table: The Curious History of Nutrition*. Oxford, UK: Oxford University Press, 2007.
- Gregory, Jane. *Fred Hoyle's Universe*. Oxford, UK: Oxford University Press, 2005.
- Gribbin, John. *The Scientists: A History of Science Told through the Lives of Its Greatest Inventors*. New York: Random House, 2003.
- Gribbin, John, and Mary Gribbin. *Stardust: Supernovae and Life—the Cosmic Connection*. New Haven, CT: Yale University Press, 2001.
- Hagmann, Michael. "Between a Rock and a Hard Place." *Science* 295, no. 5562 (March 15, 2002).
- Haldane, J.B.S. *Possible Worlds*. London: Chatto and Windus, 1927.
- Hammond, Allen L. *A Passion to Know: 20 Profiles in Science*. New York: Scribner's, 1984.
- Hanson, Norwood Russell. "Discovering the Positron (I)." *British Journal for the Philosophy of Science* 12, no. 47 (November 1961).
- Harder, Ben. "Water for the Rock." *Science News* 161, no. 12 (March 23, 2002).
- Hargittai, Balazs, and Istvan Hargittai. *Candid Science V: Conversations with Famous Scientists*. London: Imperial College Press, 2005.
- Harold, Franklin M. *To Make the World Intelligible*. Altona, Manitoba, Canada: FriesenPress, 2017.
- Hart, Matthew. *Gold: The Race for the World's Most Seductive Metal*. New York: Simon & Schuster, 2013.
- Harvie, David I. *Limeys: The True Story of One Man's War against Ignorance, the Establishment and the Deadly Scurvy*. Stroud, Gloucestershire, UK: Sutton Publishing, 2002.
- Hawkes, Peter W. "Ernst Ruska." *Physics Today* 43, no. 7 (July 1990).
- Hazen, Robert M. *Genesis: The Scientific Quest for Life's Origin*. Washington, DC: National Academies Press, 2005.
- . *The Story of Earth: The First 4.5 Billion Years, from Stardust to Living Planet*. New York: Penguin Books, 2013.
- Heap, Sir Brian, and Gregory Gregoriadis. "Alec Douglas Bangham, 10 November 1921–9 March 2010." *Biographical Memoirs of Fellows of the Royal Society* 57 (December 1, 2011).

Bibliography

- Hedesan, Georgiana D. "The Influence of Louvain Teaching on Jan Baptist Van Helmont's Adoption of Paracelsianism and Alchemy." *Ambix* 68, no. 2–3 (2021).
- Helmholtz, Hermann von. *Science and Culture: Popular and Philosophical Essays*. Chicago: University of Chicago Press, 1995.
- Henahan, Sean. "From Primordial Soup to the Prebiotic Beach: An Interview with the Exobiology Pioneer Dr. Stanley L. Miller." National Health Museum, Accessexcellence.org, October 1996.
- Herculano-Houzel, Suzana. "The Human Brain in Numbers: A Linearly Scaled-Up Primate Brain." *Frontiers in Human Neuroscience* 3 (November 2009).
- "Hermann Hellriegel." *Nature* 53, no. 1358 (November 7, 1895).
- Hockey, Thomas, Virginia Trimble, et al., eds. "Gilbert, William," in *Biographical Encyclopedia of Astronomers*. New York: Springer, 2014.
- Hoffman, Paul. "Recent and Ancient Algal Stromatolites," in *Evolving Concepts in Sedimentology*, ed. Robert N. Ginsburg. Baltimore: Johns Hopkins University Press, 1973.
- Hoffmann, Peter M. *Life's Ratchet: How Molecular Machines Extract Order from Chaos*. New York: Basic Books, 2012.
- Hofmann, August Wilhelm von. *The Life-Work of Liebig*. London: Macmillan, 1876.
- Hom, Jennifer, and Shey-Shing Sheu. "Morphological Dynamics of Mitochondria: A Special Emphasis on Cardiac Muscle Cells." *Journal of Molecular and Cellular Cardiology* 46, no. 6 (June 2009).
- Honegger, Rosmarie. "Simon Schwendener (1829–1919) and the Dual Hypothesis of Lichens." *The Bryologist* 103, no. 2 (2000).
- Hopkins, Frederick Gowland. *Newer Aspects of the Nutrition Problem*. New York: Columbia University Press, 1922.
- Horgan, John. "Francis H. C. Crick: The Mephistopheles of Neurobiology." *Scientific American* 266, no. 2 (1992).
- . "From My Archives: Quark Inventor Murray Gell-Mann Doubts Science Will Discover 'Something Else.'" *Scientific American Blog*, December 17, 2013. <https://blogs.scientificamerican.com/cross-check/from-my-archives-quark-inventor-murray-gell-mann-doubts-science-will-discover-e2809csomething-elsee2809d>.
- . "Remembering Big Bang Basher Fred Hoyle." *Scientific American Blog*, April 7, 2020, <https://blogs.scientificamerican.com/cross-check/remembering-big-bang-basher-fred-hoyle/>.
- Houston, Peterson. *A Treasury of the World's Great Speeches*. New York: Simon & Schuster, 1954.
- Howard Hughes Medical Institute. *The Discovery of Ribozymes*, HHMI BioInteractive video interview with Thomas Cech, 1995, <https://www.biointeractive.org/classroom-resources/discovery-ribozymes>.
- Hoyle, Fred. *Home Is Where the Wind Blows: Chapters from a Cosmologist's Life*. Mill Valley, CA: University Science Books, 1994.
- . *The Small World of Fred Hoyle: An Autobiography*. London: Michael Joseph, 1986.

Bibliography

- Hughes, David. "Fred L. Whipple 1906–2004." *Astronomy & Geophysics* 45, no. 6 (December 1, 2004).
- Hunter, Graeme. *Vital Forces: The Discovery of the Molecular Basis of Life*. San Diego: Academic Press, 2000.
- Ingenhousz, Jan. *An Essay on the Food of Plants and the Renovation of Soils*. London: Bulmer and Co., 1796.
- . *Experiments upon Vegetables: Discovering their great Power of purifying the Common Air in the Sun-shine and of Injuring it in the shade and at Night, to which is joined a new Method of examining the accurate Degree of Salubrity of the Atmosphere*. London: Elmsly and Payne, 1779.
- Interview with Albert Claude. Rockefeller Institute Archive Center, RAC FA1444 (Box 1, Folder 5), 1976.
- Jess, Allison, and Will Kendrew. "Murchison Meteorite Continues to Dazzle Scientists." ABC News, Goulburn Murray, Australia, December 28, 2016, <https://www.abc.net.au/news/2016-12-29/murchison-meteorite/8113520>.
- Jewitt, David, and Edward Young. "Oceans from the Skies." *Scientific American* 312, no. 3 (March 2015).
- Johnson, George. *Strange Beauty: Murray Gell-Mann and the Revolution in Twentieth-Century Physics*, 1st ed. New York: Knopf, 1999.
- Johnston, Harold S. *A Bridge Not Attacked: Chemical Warfare Civilian Research during World War II*. Singapore: World Scientific, 2003.
- Judson, Horace Freeland. *The Eighth Day of Creation: Makers of the Revolution in Biology*. New York: Simon & Schuster, 1979.
- Kaharl, Victoria A. *Water Baby: The Story of Alvin*. New York: Oxford University Press, 1990.
- Kahn, Sherry. "How Much Oxygen Does a Person Consume in a Day?" HowStuffWorks, May 11, 2021, <https://health.howstuffworks.com/human-body/systems/respiratory/question98.htm>.
- Kamen, Martin D. "A Cupful of Luck, a Pinch of Sagacity." *Annual Review of Biochemistry* 55, no. 1 (1986).
- . "Early History of Carbon-14." *Science* 140, no. 3567 (May 10, 1963).
- . "Onward into a Fabulous Half-Century." *Photosynthesis Research* 21, no. 3 (September 1, 1989).
- . *Radiant Science, Dark Politics: A Memoir of the Nuclear Age*. Berkeley: University of California Press, 1985.
- Kellogg, John Harvey. *The New Dietetics: What to Eat and How: A Guide to Scientific Feeding in Health and Disease*. Battle Creek, MI: Modern Medicine Publishing Company, 1921.
- Kelly, Cynthia. "John Earl Haynes's Interview." Atomic Heritage Foundation, Voices of the Manhattan Project, Oak Ridge, TN, February 6, 2017, <https://www.manhattanprojectvoices.org/oral-histories/john-earl-hayness-interview>.
- Kelvin, William Thomson. *Popular Lectures and Addresses*, vol. 2, *Geology and General Physics*. London: Macmillan, 1894.

Bibliography

- King, Elbert. *Moon Trip: A Personal Account of the Apollo Program and Its Science*. Houston: University of Houston, 1989.
- Kirschvink, Joseph, and Benjamin Weiss. "Mars, Panspermia, and the Origin of Life: Where Did It All Begin?" *Palaeontologia Electronica* 4, no. 2 (2001), https://palaeo-electronica.org/2001_2/editor/mars.htm.
- Klickstein, Herbert S. "Charles Caldwell and the Controversy in America over Liebig's 'Animal Chemistry.'" *Chymia* 4 (1953).
- Knoll, Andrew H. *A Brief History of Earth: Four Billion Years in Eight Chapters*. New York: HarperCollins, 2021.
- Kragh, Helge. "'The Wildest Speculation of All': Lemaître and the Primeval-Atom Universe," in *Georges Lemaître: Life, Science and Legacy*, ed. Rodney D. Holder and Simon Mitton. Heidelberg, Germany: Springer, 2012.
- Kraus, John. "A Strange Radiation from Above." North American AstroPhysical Observatory, *Cosmic Search* 2, no. 1 (Winter 1980).
- Krulwich, Robert. "Born Wet, Human Babies Are 75 Percent Water: Then Comes the Drying." *Krulwich Wonders*, National Public Radio, November 26, 2013.
- Kunzig, Robert. *Mapping the Deep: The Extraordinary Story of Ocean Science*. New York: Norton, 2000.
- Kursanov, A. L. "Sketches to a Portrait of A. I. Oparin," in *Evolutionary Biochemistry and Related Areas of Physicochemical Biology: Dedicated to the Memory of Academician A. I. Oparin*. Moscow: Bach Institute of Biochemistry, Russian Academy of Sciences, 1995.
- Kusek, Kristen. "Through the Porthole 30 Years Ago." *Oceanography* 20, no. 1 (March 1, 2007).
- LaCapra, Véronique. "Bird, Plane, Bacteria? Microbes Thrive in Storm Clouds." *Morning Edition*, National Public Radio, January 29, 2013.
- Lambert, Dominique. *The Atom of the Universe: The Life and Work of Georges Lemaître*. Krakow: Copernicus Center Press, 2016.
- . "Einstein and Lemaître: Two Friends, Two Cosmologies." Interdisciplinary Encyclopedia of Religion & Science (Inters.org).
- . "Georges Lemaître: The Priest Who Invented the Big Bang," in *Georges Lemaître: Life, Science and Legacy*, ed. Rodney D. Holder and Simon Mitton. Heidelberg, Germany: Springer, 2012.
- Lamm, Ehud, Oren Harman, and Sophie Juliane Veigl. "Before Watson and Crick in 1953 Came Friedrich Miescher in 1869." *Genetics* 215, no. 2 (June 1, 2020).
- Lane, Nick. *Life Ascending: The Ten Great Inventions of Evolution*. London: Profile Books, 2010.
- . *Power, Sex, Suicide: Mitochondria and the Meaning of Life*, 2nd ed. Oxford, UK: Oxford University Press, 2018.
- . *The Vital Question: Why Is Life the Way It Is?* London: Profile Books, 2015.
- . "Why Is Life the Way It Is?" *Molecular Frontiers Journal* 3, no. 1 (2019).
- Larson, Clarence. Interview with Martin Kamen, Pioneers in Science and Technology

Bibliography

- Series, Center for Oak Ridge Oral History, March 24, 1986, <http://cdm16107.contentdm.oclc.org/cdm/ref/collection/p15388coll1/id/523>.
- Laskar, Jacques, and Mickael Gastineau. "Existence of Collisional Trajectories of Mercury, Mars and Venus with the Earth." *Nature* 459, no. 7248 (June 2009).
- Lazcano, Antonio. "Alexandr I. Oparin and the Origin of Life: A Historical Re-assessment of the Heterotrophic Theory." *Journal of Molecular Evolution* 83, no. 5 (December 2016).
- Lazcano, Antonio, and Jeffrey L. Bada. "Stanley L. Miller (1930–2007): Reflections and Remembrances." *Origins of Life and Evolution of Biospheres* 38, no. 5 (October 2008).
- Lemaître, Georges. "Contributions to a British Association Discussion on the Evolution of the Universe." *Nature* 128 (October 24, 1931).
- . "My Encounters with A. Einstein," 1958, Interdisciplinary Encyclopedia of Religion & Science, <https://www.inters.org/lemaitre-einsten>.
- . *The Primeval Atom: An Essay on Cosmogony*. New York: Van Nostrand, 1950.
- Levy, David H. *David Levy's Guide to Observing and Discovering Comets*. Cambridge, UK: Cambridge University Press, 2003.
- . *The Quest for Comets: An Explosive Trail of Beauty and Danger*. New York: Plenum Press, 1994.
- Lieberman, Daniel. *The Story of the Human Body: Evolution, Health, and Disease*. New York: Vintage Books, 2014.
- Liebig, Justus. "Justus Von Liebig: An Autobiographical Sketch," trans. J. C. Brown. *Popular Science Monthly* 40 (March 1892).
- Liebig, Justus Freiherr von. *Animal Chemistry: Or Organic Chemistry in Its Application to Physiology and Pathology*, 2nd ed., William Gregory with additional notes and corrections by Dr. Gregory and others. Cambridge, MA: John Owen, 1843.
- Lind, James. *A Treatise on the Scurvy, in Three Parts: Containing an Inquiry into the Nature, Causes, and Cure of That Disease, Together with a Critical and Chronological View of What Has Been Published on the Subject*. London: Printed for S. Crowder, D. Wilson and G. Nicholls, T. Cadell, T. Becket and Co., G. Pearch, and W. Woodfall, 1772.
- Livio, Mario. *Brilliant Blunders: From Darwin to Einstein—Colossal Mistakes by Great Scientists That Changed Our Understanding of Life and the Universe*. New York: Simon & Schuster, 2013.
- Lovelock, James E. "Hands Up for the Gaia Hypothesis." *Nature* 344, no. 6262 (March 1990).
- Lucentini, Jack. "Darkness Before the Dawn—of Biology." *The Scientist* 17, no. 23 (December 1, 2003).
- MacFarlane, Thos. "The Transmutation of Nitrogen." *Ottawa Naturalist* 8 (1895).
- MacLeod, Colin. "Obituary Notice: Oswald Theodore Avery, 1877–1955." *Microbiology* 17, no. 3 (1957).
- Maddox, Brenda. *Rosalind Franklin: The Dark Lady of DNA*. London: HarperCollins, 2002.

Bibliography

- Magiels, Geerdt. "Dr. Jan IngenHousz, or Why Don't We Know Who Discovered Photosynthesis?" First Conference of the European Philosophy of Science Association, Madrid, November 15–17, 2007.
- . *From Sunlight to Insight: Jan IngenHousz, the Discovery of Photosynthesis & Science in the Light of Ecology*. Brussels: Brussels University Press, 2010.
- Maltz, Alesia. "Casimer Funk, Nonconformist Nomenclature, and Networks Surrounding the Discovery of Vitamins." *Journal of Nutrition* 143, no. 7 (July 2013).
- Mancuso, Stefano, and Alessandra Viola. *Brilliant Green: The Surprising History and Science of Plant Intelligence*. Washington, DC: Island Press, 2015.
- Margulis, Lynn. "Mixing It Up," in *Curious Minds: How a Child Becomes a Scientist*, ed. John Brockman. London: Vintage, 2005.
- Margulis, Lynn, and Dorion Sagan. *Microcosmos: Four Billion Years of Evolution from Our Microbial Ancestors*. New York: Summit Books, 1986.
- . *What Is Life?* New York: Simon & Schuster, 1995.
- Markel, Howard. *The Secret of Life: Rosalind Franklin, James Watson, Francis Crick, and the Discovery of DNA's Double Helix*. New York: Norton, 2021.
- Markham, James M. "European Spacecraft Grazes Comet." *New York Times*, March 14, 1986.
- Marsden, Brian G. "Fred Lawrence Whipple (1906–2004)." *Publications of the Astronomical Society of the Pacific* 117, no. 838 (2005).
- Marvin, Ursula B. "Fred L. Whipple," Oral Histories in Meteoritics and Planetary Science 13. *Meteoritics & Planetary Science* 39, no. S8 (August 2004).
- . "Gerald J. Wasserburg," Oral Histories in Meteoritics and Planetary Science 12. *Meteoritics & Planetary Science* 39, no. S8 (2004).
- McCarty, Maclyn. *The Transforming Principle: Discovering That Genes Are Made of DNA*. New York: Norton, 1986.
- McCosh, Frederick William James. *Boussingault: Chemist and Agriculturist*. Dordrecht, Netherlands: D. Reidel, 2012.
- Meiklejohn, Arnold Peter. "The Curious Obscurity of Dr. James Lind." *Journal of the History of Medicine and Allied Sciences* 9, no. 3 (July 1954).
- Menzel, Donald H. "Blast of Giant Atom Created Our Universe." *Modern Mechanics*, December 1932.
- Mesler, Bill, and H. James Cleaves II. *A Brief History of Creation: Science and the Search for the Origin of Life*. New York: Norton, 2016.
- Meteoritical Society. "Murchison." *Meteoritical Bulletin*, <https://www.lpi.usra.edu/meteor/metbull.php?code=16875>.
- Meuron-Landolt, Monique de. "Johannes Friedrich Miescher: sa personnalité et l'importance de son œuvre." *Bulletin der Schweizerischen Akademie der Medizinischen Wissenschaften* 25, no. 1–2 (January 1970).
- Mikhailov, V. M. *Put' k istinye [The Path to the Truth]*. Moscow, Sovetskaya Rossiia, 1984.
- Miklós, Vincze. "Seriously Scary Radioactive Products from the 20th Century."

Bibliography

- Gizmodo*, May 9, 2013, <https://gizmodo.com/seriously-scary-radioactive-consumer-products-from-the-498044380>.
- Miller, Stanley. "The First Laboratory Synthesis of Organic Compounds under Primitive Earth Conditions," in *The Heritage of Copernicus: Theories "Pleasing to the Mind,"* ed. Jerzy Neyman. Cambridge, MA: MIT Press, 1974.
- Miller, Stanley L., and Jeffrey L. Bada. "Submarine Hot Springs and the Origin of Life." *Nature* 334, no. 6183 (August 1988).
- Milo, Ron, and Rob Phillips. *Cell Biology by the Numbers*. New York: Garland Science, 2015.
- Mirsky, Alfred E. "The Discovery of DNA." *Scientific American* 218, no. 6 (1968).
- Mitton, Simon. "The Expanding Universe of Georges Lemaître." *Astronomy & Geophysics* 58, no. 2 (April 1, 2017).
- . *Fred Hoyle: A Life in Science*. New York: Cambridge University Press, 2011.
- . "Georges Lemaître and the Foundations of Big Bang Cosmology." *Antiquarian Astronomer*, July 18, 2020.
- Moberg, Carol L. *Entering an Unseen World: A Founding Laboratory and Origins of Modern Cell Biology, 1910–1974*. New York: Rockefeller University Press, 2012.
- Monroe, Linda. "2 Dispute Popular Theory on Life Origin." *Los Angeles Times*, August 18, 1988.
- Moore, Donovan. *What Stars Are Made Of: The Life of Cecilia Payne-Gaposchkin*. Cambridge, MA: Harvard University Press, 2020.
- Morbidelli, A., J. Chambers, et al. "Source Regions and Timescales for the Delivery of Water to the Earth." *Meteoritics & Planetary Science* 35, no. 6 (2000).
- Morris, Peter J. T. *The Matter Factory: A History of the Chemistry Laboratory*. London: Reaktion Books, 2015.
- Moses, Vivian, and Sheila Moses. "Interview with Al Bassham," in *The Calvin Lab: Oral History Transcript 1945–1963*, chapter 7. Bancroft Library, Regional Oral History Office, Lawrence Berkeley Laboratory, University of California–Berkeley, 2000.
- . "Interview with Rod Quayle," in *The Calvin Lab: Oral History Transcript 1945–1963*, vol. 1, chapter 3. Bancroft Library, Regional Oral History Office, Lawrence Berkeley Laboratory, University of California–Berkeley, 2000.
- Mulder, Gerardus. *Liebig's Question to Mulder Tested by Morality and Science*. London and Edinburgh: William Blackwood and Sons, 1846.
- National Geographic Channel. "Birth of the Oceans." *Naked Science* series, March 2009.
- New York Times*. "Finds Spiral Nebulae Are Stellar Systems: Dr. Hubbell [sic] Confirms View That They Are 'Island Universes' Similar to Our Own," November 23, 1924.
- . "Scientists Find Indication of a Vitamin Which Prevents Softening of the Brain," April 10, 1931.
- Nicholson, Wayne L., Nobuo Munakata, et al. "Resistance of Bacillus Endospores

Bibliography

- to Extreme Terrestrial and Extraterrestrial Environments.” *Microbiology and Molecular Biology Reviews* 64, no. 3 (September 1, 2000).
- Nobel Lectures Physics: Including Presentation Speeches and Laureates' Biographies, 1922–1941*. Amsterdam: Elsevier, 1965.
- Nutman, P. S. “Centenary Lecture.” *Philosophical Transactions of the Royal Society of London*, Series B, *Biological Sciences* 317, no. 1184 (1987).
- Olby, Robert. “Cell Chemistry in Miescher’s Day.” *Medical History* 13, no. 4 (October 1969).
- . *The Path to the Double Helix: The Discovery of DNA*. Seattle: University of Washington Press, 1974.
- Oliveira, Patrick Luiz Sullivan De. “Martyrs Made in the Sky: The *Zénith* Balloon Tragedy and the Construction of the French Third Republic’s First Scientific Heroes.” *Notes and Records: The Royal Society Journal of the History of Science* 74, no. 3 (September 18, 2019).
- Oparin, Aleksandr. *The Origin of Life*, trans. Sergius Morgulis, 2nd ed. New York: Dover, 1952.
- O’Raifeartaigh, Cormac, and Simon Mitton. “Interrogating the Legend of Einstein’s ‘Biggest Blunder.’” *Physics in Perspective* 20 (December 2018).
- Orgel, Leslie E. “Are You Serious, Dr. Mitchell?” *Nature* 402, no. 6757 (November 4, 1999).
- Otis, Laura. *Rethinking Thought: Inside the Minds of Creative Scientists and Artists*. New York: Oxford University Press, 2015.
- Pagel, Walter. *Joan Baptista Van Helmont: Reformer of Science and Medicine*. Cambridge, UK: Cambridge University Press, 1982.
- Pais, Abraham. *Inward Bound: Of Matter and Forces in the Physical World*. Oxford, UK: Clarendon Press, 1988.
- Palade, George E. “Albert Claude and the Beginnings of Biological Electron Microscopy.” *Journal of Cell Biology* 50, no. 1 (July 1971).
- Patel, Bhavesh H., Claudia Percivalle, et al. “Common Origins of RNA, Protein and Lipid Precursors in a Cyanosulfidic Protometabolism.” *Nature Chemistry* 7, no. 4 (April 2015).
- “Paul C. Aebersold Interview.” *Longines Chronoscope*, CBS, 1953. <https://www.youtube.com/watch?v=RFcxSXIUO44>.
- Payne-Gaposchkin, Cecilia. *Cecilia Payne-Gaposchkin: An Autobiography and Other Recollections*. Cambridge, UK: Cambridge University Press, 1996.
- Peretó, Juli, Jeffrey L. Bada, and Antonio Lazcano. “Charles Darwin and the Origin of Life.” *Origins of Life and Evolution of the Biosphere* 39, no. 5 (October 2009).
- Perutz, M. F. “Co-Chairman’s Remarks: Before the Double Helix.” *Gene* 135, no. 1–2 (December 15, 1993).
- Petterson, Roger. “The Chemical Composition of Wood,” in *The Chemistry of Solid Wood: Advances in Chemistry*, vol. 207. American Chemical Society, 1984.

Bibliography

- Phillips, J. P. "Liebig and Kolbe, Critical Editors." *Chymia* 11 (January 1966).
- Plitt, Charles C. "A Short History of Lichenology." *The Bryologist* 22, no. 6 (1919).
- Plumb, Robert. "Brookhaven Cosmotron Achieves the Miracle of Changing Energy Back into Matter." *New York Times*, December 21, 1952.
- Portree, David. "The *Eagle* Has Crashed (1966)." *Wired*, May 15, 2012.
- Poundstone, William. *Carl Sagan: A Life in the Cosmos*. New York: Henry Holt, 2000.
- Powell, James. "To a Rocky Moon," in *Four Revolutions in the Earth Sciences: From Heresy to Truth*. New York: Columbia University Press, 2014.
- Prebble, John. "Peter Mitchell and the Ox Phos Wars." *Trends in Biochemical Sciences* 27, no. 4 (April 2002).
- . "The Philosophical Origins of Mitchell's Chemiosmotic Concepts." *Journal of the History of Biology* 34 (2001).
- Prebble, John, and Bruce Weber. *Wandering in the Gardens of the Mind: Peter Mitchell and the Making of Glynn*. New York: Oxford University Press, 2003.
- Price, Catherine. *Vitamina: How Vitamins Revolutionized the Way We Think about Food*. New York: Penguin Books, 2016.
- Prothero, Donald R. *The Story of Life in 25 Fossils: Tales of Intrepid Fossil Hunters and the Wonders of Evolution*. New York: Columbia University Press, 2015.
- Quammen, David. *The Tangled Tree: A Radical New History of Life*. New York: Simon & Schuster, 2018.
- Racker, Efraim. "Reconstitution, Mechanism of Action and Control of Ion Pumps." *Biochemical Society Transactions* 3, no. 6 (December 1, 1975).
- Radetsky, Peter. "How Did Life Start?" *Discover*, November 1992.
- Ralfs, John. "The Lichens of West Cornwall," in *Transactions of the Penzance Natural History and Antiquarian Society*, vol. 1. Plymouth, 1880.
- Reinhard, Christopher T., Noah J. Planavsky, et al. "Evolution of the Global Phosphorus Cycle." *Nature* 541, no. 7637 (January 19, 2017).
- Rentetzi, Maria. AIP oral history interview with Leopold Halpern, March 10, 1999, <https://www.aip.org/history-programs/niels-bohr-library/oral-histories/32406>.
- . "Blau, Marietta," in *Complete Dictionary of Scientific Biography*, vol. 19. Detroit: Charles Scribner's Sons, 2008.
- . *Trafficking Materials and Gendered Experimental Practices: Radium Research in Early 20th Century Vienna*. New York: Columbia University Press, 2008.
- Rheinberger, Hans-Jörg. "Claude, Albert," in *Complete Dictionary of Scientific Biography*, vol. 20. Detroit: Charles Scribner's Sons, 2008.
- Rhodes, Richard. *The Making of the Atomic Bomb*. New York: Simon & Schuster, 1986.
- Righter, Kevin, John Jones, et al. "Michael J. Drake (1946–2011)." *Geochemical Society News*, October 1, 2011.
- Riordan, Michael. *The Hunting of the Quark: A True Story of Modern Physics*. New York: Simon & Schuster, 1987.
- Roddiss, Louis Harry. *James Lind, Founder of Nautical Medicine*. New York: Henry Schuman, 1950.

Bibliography

- Rosenfeld, Louis. "The Last Alchemist—the First Biochemist: J. B. van Helmont (1577–1644)." *Clinical Chemistry* 31, no. 10 (October 1985).
- Roskoski, Robert. "Wandering in the Gardens of the Mind: Peter Mitchell and the Making of Glynn." *Biochemistry and Molecular Biology Education* 32, no. 1 (2004).
- Rosner, Robert W., and Brigitte Strohmaier. *Marietta Blau, Stars of Disintegration: Biography of a Pioneer of Particle Physics*. Riverside, CA: Ariadne Press, 2006.
- Russell, Percy, and Anita Williams. *The Nutrition and Health Dictionary*. New York: Chapman and Hall, 1995.
- Ryan, Frank. *Darwin's Blind Spot: Evolution Beyond Natural Selection*. Boston: Houghton Mifflin Harcourt, 2002.
- Sagan, Carl. *Conversations with Carl Sagan*, ed. Tom Head. Jackson: University Press of Mississippi, 2006.
- Sagan, Dorion. *Lynn Margulis: The Life and Legacy of a Scientific Rebel*. White River Junction, VT: Chelsea Green, 2012.
- Saier, Milton H., Jr. "Peter Mitchell and the Life Force," <https://petermitchellbiology.wordpress.com/>.
- Sapp, Jan. *Evolution by Association: A History of Symbiosis*. New York: Oxford University Press, 1994.
- Schmidt, Albert. "Essai d'une biologie de l'holophyte des Lichens." *Mémoires du Muséum national d'histoire naturelle, Série B, Botanique* 3 (1953).
- Schopf, William. *Cradle of Life: The Discovery of Earth's Earliest Fossils*. Princeton, NJ: Princeton University Press, 1999.
- . *Life in Deep Time: Darwin's "Missing" Fossil Record*. Boca Raton, FL: CRC Press, 2018.
- . *Major Events in the History of Life*. Boston: Jones & Bartlett Learning, 1992.
- Schuchert, Charles. "Charles Doolittle Walcott, (1850–1927)." *Proceedings of the American Academy of Arts and Sciences* 62, no. 9 (1928).
- Segré, Daniel, and Doron Lancet. "Theoretical and Computational Approaches to the Study of the Origin of Life" in *Origins: Genesis, Evolution and Diversity of Life*, ed. Joseph Seckbach. Dordrecht, Netherlands: Springer, 2005.
- Sender, Ron, Shai Fuchs, and Ron Milo. "Revised Estimates for the Number of Human and Bacteria Cells in the Body." *PLOS Biology* 14, no. 8 (August 19, 2016).
- Sender, Ron, and Ron Milo. "The Distribution of Cellular Turnover in the Human Body." *Nature Medicine* 27, no. 1 (January 2021).
- Seward, Albert Charles. *Plant Life through the Ages: A Geological and Botanical retrospect*, 2nd ed. New York: Hafner, 1959.
- Sharkey, Thomas D. "Discovery of the Canonical Calvin-Benson Cycle." *Photosynthesis Research* 140, no. 2 (May 1, 2019).
- Shaw, Bernard. *Annajanska, the Bolshevik Empress: A Revolutionary Romancelet, in Selected One Act Plays*. Harmondsworth: Penguin, 1976.
- Shindell, Matthew. *The Life and Science of Harold C. Urey*. Chicago: University of Chicago Press, 2019.

Bibliography

- Sime, Ruth Lewin. "Marietta Blau: Pioneer of Photographic Nuclear Emulsions and Particle Physics." *Physics in Perspective* 15 (2013).
- Smith, Annie Lorrain. *Lichens*. Cambridge, UK: Cambridge University Press, 1921.
- Stager, Curt. *Your Atomic Self: The Invisible Elements That Connect You to Everything Else in the Universe*. New York: Thomas Dunne Books, 2014.
- Steinmaurer, Rudolf. "Erinnerungen an V.F. Hess, Den Entdecker der Kosmischen Strahlung, und an Die ersten Jahre des Betriebes des Hafelekar-Labors." *Early History of Cosmic Ray Studies* 118 (1985).
- Step, Edward. *Plant-Life: Popular Papers on the Phenomena of Botany*. London: Marshall Japp, 1881.
- Stevens, Charles. "The Neuron." *Scientific American* 241, no. 3 (September 1979).
- St. Louis Post-Dispatch, "Is Vitamine Starvation the True Cause of Cancer?" October 27, 1924.
- Sullivan, Walter. "Subatomic Tests Suggest a New Layer of Matter." *New York Times*, April 25, 1971.
- . *We Are Not Alone: The Search for Intelligent Life on Other Worlds*, rev. ed. New York: Dutton, 1993.
- Sundermier, Ali. "The Particle Physics of You." *Symmetry* magazine, November 3, 2015, <https://www.symmetrymagazine.org/article/the-particle-physics-of-you>.
- Tegmark, Max. "Solid. Liquid. Consciousness." *New Scientist* 222, no. 2964 (April 12, 2014).
- Telegraph, The* (London). "Lynn Margulis," December 13, 2011.
- Tera, Fouad, Dimitri A. Papanastassiou, and Gerald J. Wasserburg. "A Lunar Cataclysm at ~3.95 AE and the Structure of the Lunar Crust," in *Lunar Science IV* (1973).
- Thoreau, Henry David. *Walden*. Boston: Ticknor & Fields, 1854; Beacon Press, 2004.
- Thorpe, Thomas Edward. *Essays in Historical Chemistry*. London: Macmillan, 1902.
- Times, The* (London). "The British Association: Evolution of the Universe," September 30, 1931.
- Tobey, Ronald C. *Saving the Prairies: The Life Cycle of the Founding School of American Plant Ecology, 1895–1955*. Berkeley: University of California Press, 1981.
- Townes, Charles H. "The Discovery of Interstellar Water Vapor and Ammonia at the Hat Creek Radio Observatory," in *Revealing the Molecular Universe: One Antenna Is Never Enough*, Proceedings of a Symposium Held at University of California, Berkeley, California, USA, September 9–10, 2005. Astronomical Society of the Pacific.
- . *How the Laser Happened: Adventures of a Scientist*. New York: Oxford University Press, 2002.
- . "Microwave and Radio-Frequency Resonance Lines of Interest to Radio Astronomy," in *International Astronomical Union Symposium*, no. 4, *Radio Astronomy*. Cambridge, UK: Cambridge University Press, 1957.
- "Tracing the Lost Railway Lines of Indonesia: The Forgotten Steamtram of Bat-

Bibliography

- avia,” <https://indonesialostrailways.blogspot.com/p/the-forgotten-steamtram-of-batavia.html>.
- Trewavas, Anthony. “The Foundations of Plant Intelligence.” *Interface Focus* 7, no. 3 (June 6, 2017).
- . “Mindless Mastery.” *Nature* 415, no. 6874 (February 21, 2002).
- Trewavas, Anthony, and František Baluška. “The Ubiquity of Consciousness.” European Molecular Biology Organization, *EMBO Reports* 12, no. 12 (December 1, 2011).
- Turner, R. Steven. “Justus Liebig versus Prussian Chemistry: Reflections on Early Institute-Building in Germany.” *Historical Studies in the Physical Sciences* 13, no. 1 (1982).
- USDA FoodData Central website. “Bananas, Ripe and Slightly Ripe, Raw,” April 1, 2020, <https://fdc.nal.usda.gov/fdc-app.html#/food-details/1105314/nutrients>.
- Valley, John W. “A Cool Early Earth?” *Scientific American* 293, no. 4 (October 2005).
- Van Klooster, H. S. “Jan Ingenhousz.” *Journal of Chemical Education* 29, no. 7 (July 1, 1952).
- Vedder, Edward Bright. *Beriberi*. New York: William Wood, 1913.
- Vernadsky, Vladimir I. *The Biosphere*, ed. Mark Mcmenamin, trans. David Langmuir. New York: Copernicus, 1998.
- Von Braun, Wernher, Fred L. Whipple, and Willy Ley. *Conquest of the Moon*, ed. Cornelius Ryan. New York: Viking Press, 1953.
- Wächtershäuser, Günter. “Before Enzymes and Templates: Theory of Surface Metabolism.” *Microbiological Reviews* 52, no. 4 (December 1988).
- . “The Origin of Life and Its Methodological Challenge.” *Journal of Theoretical Biology* 187, no. 4 (August 21, 1997).
- Wade, Nicholas. “Heart Muscle Renewed over Lifetime, Study Finds.” *New York Times*, April 2, 2009.
- . “Making Sense of the Chemistry That Led to Life on Earth.” *New York Times*, May 4, 2015.
- . “Meet Luca, the Ancestor of All Living Things.” *New York Times*, July 25, 2016.
- . “Stanley Miller, Who Examined Origins of Life, Dies at 77.” *New York Times*, May 23, 2007.
- . “Your Body Is Younger Than You Think.” *New York Times*, August 2, 2005.
- Wagener, Leon. *One Giant Leap: Neil Armstrong’s Stellar American Journey*. Brooklyn, NY: Forge Books, 2004.
- Walcott, Charles Doolittle. *Pre-Cambrian Fossiliferous Formations*. Rochester, NY: Geological Society of America, 1899.
- . “Pre-Carboniferous Strata in the Grand Canyon of the Colorado, Arizona.” *American Journal of Science* 26 (December 1883).
- . “Report of Mr. Charles D. Walcott, July 2,” in *Fourth Annual Report of the*

Bibliography

- Director of the United States Geological Survey*. Washington, DC: US Government Printing Office, 1885.
- Wald, George. Nobel Banquet Speech, Nobel Prize in Physiology or Medicine 1967, Stockholm, December 10, 1967.
- Walker, Gabrielle. *Snowball Earth: The Story of the Great Global Catastrophe That Spawned Life as We Know It*. New York: Crown, 2003.
- Walker, John. *Fuel of Life*, video recording of Nobel Laureate Lecture, 2018, https://www.royalacademy.dk/en/ENG_Foredrag/ENG_Walker.
- Walker, Timothy. *Plants: A Very Short Introduction*. Oxford, UK: Oxford University Press, 2012.
- Walter, Michael. "From the Discovery of Radioactivity to the First Accelerator Experiments," in *From Ultra Rays to Astroparticles: A Historical Introduction to Astroparticle Physics*, ed. Brigitte Falkenburg and Wolfgang Rhode. Dordrecht, Netherlands: Springer, 2012.
- Watson, James D., and Andrew Berry. *DNA: The Secret of Life*. New York: Knopf, 2003.
- Watson, James D., Alexander Gann, and Jan Witkowski. *The Annotated and Illustrated Double Helix*. New York: Simon & Schuster, 2012.
- Weaver, Kenneth. "What the Moon Rocks Tell Us." *National Geographic*, December 1969.
- Web of Stories. Interview with Francis Crick, "Molecular Biology in the Late 1940s," 1993, <https://www.webofstories.com/people/francis.crick/33?o=SH>.
- Web of Stories. Interview with James Watson, "Complementarity and My Place in History," 2010, <https://www.webofstories.com/people/james.watson/29?o=SH>.
- Webb, Richard. "Listening for Gravitational Waves from the Birth of the Universe." *New Scientist*, March 16, 2016.
- Weiner, Charles. AIP oral history interview with William Fowler, February 6, 1973, <https://www.aip.org/history-programs/niels-bohr-library/oral-histories/4608-4>.
- Weiss, Benjamin P., Joseph L. Kirschvink, et al. "A Low Temperature Transfer of ALH84001 from Mars to Earth." *Science* 290, no. 5492 (October 27, 2020).
- West, Bert. "Moon Rocks Go to Experts on Friday." *Newsday*, September 10, 1969.
- Wetherill, George W. "Contemplation of Things Past." *Annual Review of Earth and Planetary Sciences* 26, no. 1 (1998).
- . "The Formation of the Earth from Planetesimals." *Scientific American* 244, no. 6 (June 1981).
- Whipple, Fred L. "Of Comets and Meteors." *Science* 289, no. 5480 (August 4, 2000).
- Wilford, John Noble. "Moon Rocks Go to Houston; Studies to Begin Today: Lunar Rocks and Soil Are Flown to Houston Lab." *New York Times*, July 26, 1969.
- Wilkins, Maurice. *Maurice Wilkins: The Third Man of the Double Helix: An Autobiography*. Oxford, UK: Oxford University Press, 2005.

Bibliography

- Williams, Gareth. *Unravelling the Double Helix: The Lost Heroes of DNA*. London: Weidenfeld & Nicolson, 2019.
- Wills, Christopher, and Jeffrey Bada. *The Spark of Life: Darwin and the Primeval Soup*. Oxford, UK: Oxford University Press, 2000.
- Wilson, Charles Morrow. *Roots: Miracles Below*. New York: Doubleday, 1968.
- Wolchover, Natalie. "Geological Explorers Discover a Passage to Earth's Dark Age." *Quanta Magazine*, December 22, 2016.
- Woodard, Helen Q., and David R. White. "The Composition of Body Tissues." *British Journal of Radiology* 59, no. 708 (December 1986).
- Yarris, Lynn. "Ernest Lawrence's Cyclotron: Invention for the Ages." Lawrence Berkeley National Laboratory, Science Articles Archive, <https://www2.lbl.gov/Science-Articles/Archive/early-years.html>.
- Yochelson, Ellis Leon. *Charles Doolittle Walcott, Paleontologist*. Kent, OH: Kent State University Press, 1998.
- Yong, Ed. "Trees Have Their Own Internet." *The Atlantic*, April 14, 2016.
- Zahnle, Kevin, Laura Schaefer, and Bruce Fegley. "Earth's Earliest Atmospheres." *Cold Spring Harbor Perspectives in Biology* 2, no. 10 (October 2010).
- "The Zenith Tragedy: The Dangers of Hypoxia." Those Magnificent Men in Their Flying Machines, <https://www.thosemagnificentmen.co.uk/balloons/zenith.html>.
- Ziegler, Charles A. "Technology and the Process of Scientific Discovery: The Case of Cosmic Rays." *Technology and Culture* 30, no. 4 (October 1989).
- Zimmer, Carl. "Vitamins' Old, Old Edge." *New York Times*, December 9, 2013.
- Zimmermann, Albrecht. "Nachrufe: Simon Schwendener." *Berichte der Deutschen Botanischen Gesellschaft* 40 (1922).
- Zweig, George. "Origin of the Quark Model," in *Proceedings of the Fourth International Conference on Baryon Resonances*, Toronto, July 14–16, 1980.