A World from Dust Discussion Guide for Chemistry Classes

First in this document are discussion questions organized by chapter. Each section starts with a specific set of recall questions that students can answer to refresh memory of the chapter itself. General discussion questions follow, then specific questions targeted toward physical chemistry [P-chem] students, and toward biochemistry [Biochem] students.

Many of these questions were raised in my physical chemistry and biochemistry classes, so they represent the students' thinking and the questions they wanted to talk about in order to put all this together. As the teacher, sometimes I had to say I don't know but talk about how we could – speculation is a valid outcome!

In addition to these questions, specific activities have been developed for particular types of chemistry courses:

First-year activities focus on recapping the scientific material from each chapter, and on practicing scientific writing at different levels.*

Physical chemistry course activities include four "Data Talks" that present the data from journal articles to the class. These data both illustrate particular points from *A World from Dust* and connect the reading to specific physical chemistry concepts such as entropy or kinetics, which occur in the order that most textbooks use. Some concepts from the Data Talks were incorporated into specific exam questions. The Physical Chemistry course plan culminates in a final presentation assignment given to the students.

Biochemistry course activities include four presentations assigned to the students of increasing complexity and difficulty, some involving independent literature searches. For the last two presentations, student engagement is enhanced by assigning the students to write quiz questions for their own presentation, and then collating those questions into a quiz given to the class during a class period following the presentations. In this way, *A World from Dust* provides a narrative connecting the four presentations.

* The complete first-year course guide will be available in 2017.

Chapter 1: Arsenic Life?

1. [Recap] List how and why Mono Lake chemistry is different; why arsenic cannot be used in DNA; how cells defend themselves against arsenic; why phosphate and magnesium work well together; Gould's "Tape of Life" quotes (it would be best to discuss in the context of Gould's own words).

2. Had you heard of the arsenic life controversy before reading this book? What did you remember about it? Many times the positive press conference is easier to remember than the negative disproof. What other pieces of news show this tendency for a lie to travel halfway around the world while the truth is still lacing up its shoes (to paraphrase Mark Twain)?

3. What did you observe about the nature of science in the "arsenic life" story? What incentives motivated the scientists as they worked to answer the question of how life used arsenic in Mono Lake? (One piece of data that may reveal a real-world motivation is the report that Felisa Wolfe-Simon named GFAJ-1 as an acronym for "Get Felisa a Job.")

4. How do you get your science news? When you hear a story, what level of proof do you need – whom do you trust most? Have you ever trusted a science news story (or April Fool's joke) that you later found out was wrong? Did that change how you read stories or what you look for?

5. What movies have you seen or stories have you read about repeating the past and getting a different outcome? Are these about repeating natural events or about repeating human choices? (Some examples are the movies *A Wonderful Life* and *Groundhog Day*, Dickens's *A Christmas Carol*, the movie *Edge of Tomorrow/Live, Die, Repeat*/novel *All You Need is Kill*, and the book/TV Series *11-22-63* by Stephen King – but most of these focus on history, not prehistory.)

6. [P-Chem] Discuss the kinetics of phosphate and why it's used the way it is, after reading Randy B. Stockbridge and Richard Wolfenden, "Hydrolysis by Nonenzymatic Catalysts and Enhancement of the Rate of Pyrophosphate by Inorganic Pyrophosphatase" J.Biol.Chem. (2011); doi: 10.1074/jbc.M110.214510

7. [Biochem] Discuss the specific benefits of phosphate after reading this paper: "Why nature chose phosphate to modify proteins" by Tony Hunter, *Phil.Trans.Roy.Soc.B* (2012) DOI: 10.1098/rstb.2012.0013

8. [Biochem] Discuss how the four experiments on pp. 7-9 combined, each with its specific strengths and weaknesses. All of these took place in a lab, not in Mono Lake itself, but each can look into the cell in a new way.

9. [Biochem] Investigate the evolution of arsenic resistance mechanisms and/or how the chemistry of the environment affects evolution.

Chapter 2: Predicting the Chemistry Inside a Cell (this chapter is more biochem than p-chem)

1. [Recap] List the different ways from this chapter in which electric charge on an element determines what will happen. Other concepts for recap include the Central Dogma, the unique qualities of sulfur, reactive oxygen species and antioxidants, how breathing depends on metal, and protein design.

2. Describe a time when you walked into a new structure, like *ekko.* What do you look at first? Were you ever surprised by what you found inside? If you didn't have verbal clues, what kind of tests could you run on a structure like *ekko* to find out more about it?

3. Discuss "redox" reactions and the relationship between oxygen, electrons, structures, and energy. What does the idea of electron balance really mean? Would we ever "run out" of electrons (and why not)? How do sulfur-rich molecules like glutathione work? Why do we call things "antioxidants" rather than "reductants"? And how effective do you expect ingesting antioxidants to be in real life?

4. What are the different artworks that appear in this chapter? Possible extension: Design an art installation like The Microbe That Learned to Reject Gold. Think about the Irving-Williams series of chemical "stickiness" and how that might interact with the proteins from something living, for example.

5. [P-Chem] Discussions of metalloenzymes and the Accidental Enzyme could be correlated with class discussions of how catalysts change free energy. It would be interesting to discuss how a metal changes free energy vs. how an enzyme site changes free energy for advanced students.

6. [P-Chem or Biochem] Do an online literature search for "Irving-Williams series" and find a paper that discusses how it works or doesn't work in a particular chemical or biochemical situation.

7. [Biochem] Investigate the literature on how available elements have shaped evolution.

8. [Biochem] Investigate the accidental enzyme, and look for other accidental enzymes, starting with the references from this section. Michael Hecht's lab has interesting references on this.

9. [Biochem] Switching metals like the beetle enzyme on p.36: Read the referenced paper and discuss how this worked. Why did life not choose this more? Then again, if it did, how would we know? Could this happen more in more extreme environments? Advanced students can also discuss the "cambialistic" enzymes (non-specific metalloenzymes) in evolutionary sequence discussed by Dupont *et al.* in "History of biological metal utilization inferred through phylogenomic analysis of protein structures." *Proc Natl Acad Sci U S A.* 2010 Jun 8;107(23):10567-72. doi: 10.1073/pnas.0912491107. (This reference will return in Chapter 6)

Chapter 3: Unfolding the Periodic Table (this chapter is more p-chem than biochem)

1. [Recap] Why does the periodic table take the shape it does? How are electron orbitals shaped (and how is this like music)? How did stars make elements? What are the Big Six elements and why are they so prevalent in rocks? Why did the moon stop evolving (geologically)?

2. How have you seen math shape chemistry (or physics, or biology)? Which equations have you ever thought about or used in a real-life situation? Which equations were the most useful to you? (Metric conversions when driving in Canada, for example)

3. What do you remember about geology exhibits in museums and how they are organized? What makes for a good geology exhibit?

4. What does entropy mean? Both at a literal and a metaphorical level. Why do things still come together if there is a universal tendency to spread out (as expressed in the 2^{nd} Law of Themodynamics)? If the universe started hot, where did all that heat "go"?

5. Why did nature select carbon and not silicon, since silicon is still very abundant and can form four bonds, plus bond itself, like carbon can?

6. In what ways is element formation a process governed by chance? In what ways is it predictable? For advanced students, could show graph of how the nucleus of Fe is more stable than other elements to show Fe is at the thermodynamic minimum, yet we have many other elements than Fe. This could go many directions, such as the concept of normal distribution and the deep relationship between entropy and probability.

7. Why do transition metals like Fe have the ability to switch charges? Consider d orbitals, overall size, and low-spin/high-spin energy levels for Fe. In context of hemoglobin.

8. How likely was the impact hypothesis? Is there recent exoplanet data about this? What can we tell from the moons in the rest of the solar system?

9. [P-Chem, after quantum mechanics] Summarize, where does the 1, 3, 5, 7 pattern in the periodic table actually come from? Or for other students teach about where the 2n+1 rule comes from.

10. [P-chem] Look up the chain of reactions by which elements are made in the sun and locate the formation of carbon from beryllium, where Hoyle's "resonant" energy level comes into play. What other reactions could form carbon and how likely are they?

11. [P-Chem] Explain Fig 3.3's "negative abundance" (p.47) to describe what negative logs mean.

12. [P-Chem] What's going on with the carbon bar in Figure 3.5 (p.56) – why does it drop below the 0 line? (This has to do with carbon's unusual positive heat of formation in this case.)

Chapter 4: The Triple-Point Planet (more p-chem than biochem)

1. [Recap] Discuss something you learned about the different planets or moons: Mars, Venus, Titan, Triton, and Europa. Other concepts include energies of combustion and concentrations.

2. What recent finding about our solar system could have been discussed in this chapter? For example, the New Horizons probe has recently discovered many new things about Pluto, which NASA and Sky & Telescope discuss at an accessible level.

3. What stories have you seen or read about humans surviving off the planet earth with near-present-day technology? Examples include *The Martian* and *Seveneves*.

4. Compare the prospects for life on Titan, Europa, another moon, and ancient Mars (with time travel added in to the speculation). Where would you send the space vessel?

5. Discuss the borderline of flow and consistency (p.79): Look up the reference for Caleb Sharf's Scientific American article on this. Does this change our view on the likelihood of life, or intelligent life, in the universe? How likely is it to be on this border?

6. Discuss how you react to the Arthur C. Clarke quote on p.79. Which way do you think we are? How would it change things for you to prove that we were the other way?

7. The Compound Interest blog has a very useful infographic titled "The Atmospheres of the Solar System." (http://www.compoundchem.com/2014/07/25/planetatmospheres/) This could be the jumping-off point for discussions or homework/test problems involving partial pressures.

8. Element Concentrations "Great Chain" Figure 4.5 (p.84): Look at the other elements listed but not mentioned in the test. Which other elements were available for use by life? Can you come up with reasons why these chemicals were not used?

9. [P-Chem] What other tree-like structures can you think of? Discuss what aspect of energy or matter flow these are maximizing.

10. [P-chem] Deduce other liquid possibilities from a table of triple points. List of planets and find which planet could have liquids?

11. [P-chem] Calculate energetic values comparing energetic gains from different molecules to try and find a molecule better than oxygen at providing energy. Also relate to "Why Fire is Hot" paper from Data Talk 2.

12. [P-Chem] Calculate energetic parameters such as entropy for reactions from this chapter. One possibility is H2O (g) → H2 (g) + O2 (g) (the reaction that allows hydrogen escape) and compare to H2O (l).

13. [Biochem] Research and discuss the unique chemical properties of H2O and compare to other possible solvents for life. One interesting paper along these line is "Membrane alternatives in worlds without oxygen: Creation of an azotosome" by Stevenson *et al.* in *Science Advances,* DOI: 10.1126/sciadv.1400067.

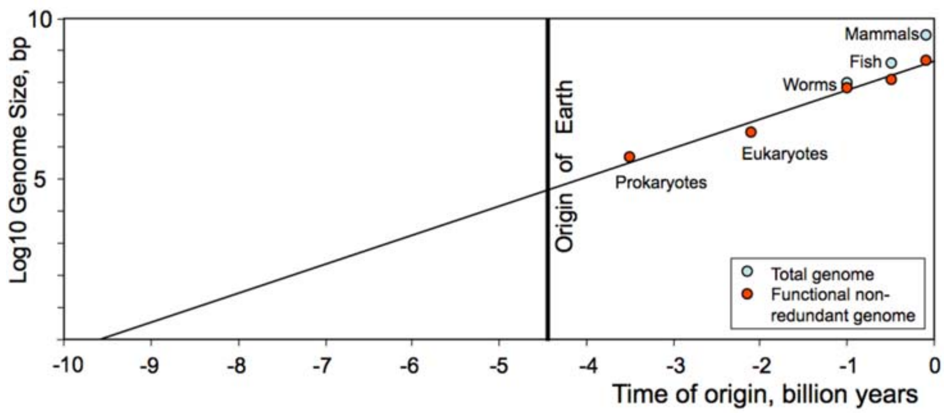
Chapter 5: Seven Chemical Clues to First Life (more biochem than p-chem)

1. [Recap] List the seven clues. (Which one is your favorite?) Describe the special characteristics of iron and which chemistry this element made possible.

2. Which experiment did you find most convincing as a possible origin of life? Which one least convincing? Do you lean toward metabolism-first or replication-first? Why?

3. Caves and Fort Casey illustrate calcium carbonate chemistry. What others examples of this chemistry can you think of?

4. What is your reaction to the surprising speed of life's origin? For example, Sharov and Gordon apply Moore's law to genetic complexity in an article titled "Life Before Earth" and conclude that life must have started before the Earth was formed, then migrated here in a process called "panspermia." arXiv:1304.3381 [physics.gen-ph]



5. Where did Earth's water come from? (The traditional answer is comets but some recent findings have suggested that a lot came from within the new planet.)

6. What does it mean that when early earth conditions are more precisely replicated, more life-like molecules are made?

7. [Biochem] Investigate one of the seven clues in detail. Use Google Scholar to find which recent papers have cited a paper from the reference section and what has happened since publication.

8. [Biochem] Locate iron-sulfur enzymes such as aconitase and research their activity and evolution. Where are iron-sulfur enzymes located?

9. [Biochem] How did early cells maintain their osmotic balance? An interesting possibility is discussed by Lane and Martin in "The origin of membrane bioenergetics." *Cell*. doi: 10.1016/j.cell.2012.11.050.

10. [Biochem] Why are amino acids in particular found on meteorites? There are so many: Would other amino acids be present in life on other planets?

Chapter 6: Wheels Within Wheels

1. [Recap] Describe the special characteristics of nickel, tungsten, or cobalt, and which chemistry this element made possible. Also discuss how anaerobic (oxygen-free) life differs from what we're used to. Recap the Great Nickel Famine from the end of the chapter.

2. Research more on Blood Falls and find other areas where "weird life" changes the landscape.

3. What does the nickel famine show about the relationship of geology to biology? What do you think it demonstrates about the "contingency" of life?

4. Compare and contrast the nickel famine in this chapter to the arsenic life story in Chapter 1. How can we tell when something like nickel or phosphate is crucial vs. when it can be substituted for?

5. Given that Titan is methane-rich and methanophages eat methane, what other conditions stand in the way of a methanophage surviving on Titan?

6. [P-chem or Biochem] Trace the energetics of the reactions in an anaerobic pathway like the Wood-Ljungdahl pathway. Why isn't every step exoergic?

7. [Biochem] Look up the papers referenced in the subsection titled "Early Earth Chemistry is Written in Our Genes." Discuss the implications and limits of the data, and how the three papers from Dupont, Caetano-Anolles, and David and Alm complement each other, and the points where they disagree.

8. [Biochem] Every circle of reactions is at least a potential wheel. How many different "levels" of wheels (or circles of reactions) can you identify? At the highest level, plants and animals produce and consume O2. At the ecosystem level, predator, prey, plants, and microbes are related. At the organism level, the organs are related with wheels, and at the biochemical level, wheels such as the citric acid cycle can be drawn. How are these wheels similar and different? How do the microbe wheels, especially in Figure 6.3, fit into this? How can wheels help us understand nature?

9. [Biochem] Investigate an anaerobic microbe's weird chemistry. What special chemical transformations does this microbe accomplish (like the Wood-Ljungdahl pathway), and can you find which metals it uses to do those reactions? Where does that microbe live? What other microbes does it need or is it related to?

10. [Biochem or P-Chem] Research other metals in porphyrins, whether in a living context (biochem) or a non-living context such as nanodevices (P-chem). Are there other reasons why we may not use copper or zinc porphyrins? What is the difference between them?

Chapter 7: The Risk and Reward of Sunlight

1. [Recap] Describe the special characteristics of manganese and which chemistry this element made possible. Also recap the different kinds of bacteria and pigment molecules encountered in this chapter.

2. What are the two functions that pigment molecules served? How does a molecule like this (one that can do more than one thing) help life adapt and develop new chemical abilities?

3. Since magnesium is associated with leaves' green color, what happens to it in the autumn when the leaves lose their green color? In plants with magnesium deficiency, the area between leaf veins yellows while the veins themselves stay green – why is this?

4. Compare and contrast green and purple photosystems. How do their different colors relate to what they do? // Compare and contrast green plastids and red mitochondria. How do their different colors relate to what they do?

5. At some points, the oceans and/or land change color in this story. Where and when? What are the colors you can see on a satellite ocean map today? What kind of catastrophic chemical spills could change the ocean's color with chemistry (with undoubtedly dire environmental consequences!)?

6. [P-chem] For Fig.7.1 (p.138), the spectra of different pigments may be worked into various homework/test problems. For example, what is the minimum number of pigments that can be used to cover all wavelengths from 400 to 700 nm?

7. [P-chem] Use Table 7.1 (p.143) to discuss the energy of passing electrons from one place to another using free energy calculations. For example, what are the only two molecules on the list that can pass electrons to NADH spontaneously? (Ferredoxin and Hydrogen)

8. [P-chem] Investigate the chemistry of the different forms of manganese, why it has five colors and how it acts as an internal shield.

9. [P-chem] Research the latest on the artificial leaf from Daniel Nocera's lab and other researchers.

10. [Biochem] Investigate the structure and mechanism of rhodopsin and its evolution.

11. [Biochem[Investigate the evolutionary connections between cholesterol, evolution, and oxygen. For example, see Brown and Galea, "Cholesterol as an evolutionary response to living with oxygen." Evolution. 2010 doi: 10.1111/j.1558-5646.2010.01011.x.

12. [Biochem] Read the referenced paper by Caetano-Anolles and colleagues from p.146 describing how the first manganese enzymes may have evolved.

Chapter 8: One Step Back, Two Steps Forward

1. [Recap] What do we see molybdenum, copper, and zinc doing in this chapter? Describe the special characteristics of each and which chemistry that element made possible. List the ways in which oxygen is a "double-edged sword."

2. Oxygen was both a direct and indirect threat to life. As a direct threat, it created reactive oxygen species (ROS). How did cells respond to this? As an indirect threat, it removed hydrogen-rich food sources. How did cells response to this? Which do you think was worse, the direct or indirect threat?

3. Why is there a "nitrogen fixation pathway," but no "magnesium fixation pathway"?

4. Why did Banded Iron Formations stop forming, considering that oxygen is still around today at high enough levels to form them?

5. On page 178, copper is described as being able "to break, blow, burn, and make new." Another versatile element is iron. Looking back through the Chapters back to Chapter 4, how could iron be described with those same four words?

6. Why is copper so much more prevalent than silver on a cellular level? It appears able to do much of the same chemistry. Why, in general, does life prefer the upper levels of the periodic table?

7. Investigate the report of the multicellular animal that lives without oxygen and has hydrogenosomes. (Danovaro *et al., BMC Biology*, "The first metazoa living in permanently anoxic conditions" DOI: 10.1186/1741-7007-8-30) Weigh the evidence for this report – to my knowledge there are no other similar reports. Consider how unusual this must be. What does oxygen provide that makes multicellular life possible?

8. Using Figure 8.4 on p.172, list the ways the earth changed as it oxidized. How does the arrow in this chapter compare and contrast with the "Arrow through the Sky" in Chapter 4? How does it relate to Figure 6.3?

9. Page 180: The lead poisoning disaster in Flint, Michigan in 2015 was an example of sticky metals sticking where they're not supposed to. Where does the lead stick to cause the symptoms? Why is it sometimes safe (or at least more safe) to shower in water that is too contaminated to drink? What is the role of Fe(III) in the form of $FeCl_3$? (Compound Interest has an excellent infographic at http://www.compoundchem.com/2016/01/25/flint-water/.)

10. [Biochem] What specific genetic changes could we look for to find evidence for the oxygen increase?

Chapter 9: Cracked Open and Knit Together by Oxygen

1. [Recap] Describe the special characteristics of calcium and which chemistry this element made possible. What was the Cambrian Explosion? List the arguments made regarding the Cambrian Explosion.

2. What is the current state of knowledge with whether oxygen is a cause or effect of the Cambrian Explosion among scientists? With a historical science like geology, how do we tell the difference between causation and correlation? Think of Butterfield's arguments. What data would resolve the situation?

3. Discuss the consistency of science. Some argue that we should not expect the universe to be rational or consistent, for example, in physics for realms far from our common experience. Also, what we can know or predict has major effects on which policy course we should take. Although a vast majority of scientists support measures to mitigate climate change, a vocal minority of scientists argues that the effects of climate change are unknowable and/or more beneficial than detrimental. What happens when a proposed cause is too simple? What happens when a scientist concludes that the cause of an event is unknowable, or that there are so many causes we can't know them all? Which is the greater danger to science?

4. Investigate how extinctions may be related to oxygen levels dropping. Ward and Kirschvink discuss this in their book *A New History of Life*, and it is discussed in the scientific literature.

5. [Biochem] On p.207 Lane's argument is presented that "mitochondria allowed the energy for genome expansion a billion years before oxygen." This was disputed by Michael Lynch, prompting a back-and-forth series of letters in *PNAS*. Trace this thread, starting with Lane and Martin's paper "The energetics of genome complexity" in *Nature*. doi: 10.1038/nature09486; then see Lynch and Marinov's paper "The bioenergetic costs of a gene" in PNAS doi: 10.1073/pnas.1514974112 and the subsequent comments by both authors in PNAS in 2016. Where do you side?

6. [Biochem] Research how small hormones are made, like dopamine. Where is oxygen added? By metal enzymes or not? Compare to cholesterol biosynthesis.

Chapter 10: The Return of the Exiled Elements

1. Describe the special characteristics of sodium and potassium and which chemistry these elements made possible. How do brains work? (An animated version of Fig. 10.3 is available at http://spu.edu/depts/its/neural_transmission.html.) How could extinction bring life? What examples are given of convergence?

2. Isaac Asimov has written a short story called "Sucker Bait" in which space adventurers are poisoned by beryllium dust. How would beryllium interfere with cellular processes? Look at Figure 3.3 and hypothesize about what the likelihood of forming a beryllium-rich planet.

3. How do Bejan's ideas about the predictability of branching structures fit with evolutionary convergence as described in Chapter 9?

4. Can a jellyfish think? Is it basically a chemical robot? What about other organisms?

5. Page 212: It appears that calcium moves with intentionality to produce certain results. How does a chemical series of events make calcium move with apparent intentionality? How does calcium work in muscles?

6. Page 223: Brains and DNA are compared. What makes this comparison appropriate despite the fact that brains are organs (which contain DNA!) and DNA is a molecule? Compare to recent publication "The Brain is Not a Computer" https://aeon.co/essays/your-brain-does-not-process-information-and-it-is-not-a-computer and response "Since the Brain's Not a Computer, What Is It?" http://www.wired.com/beyond-the-beyond/2016/05/since-brains-not-computer/

7. [Biochem] Page 226: Sodium and calcium channels are described as interconvertible. What are the exact structural changes and mechanism that allow this? How does an organism stay alive during this process?

8. [Biochem] Investigate how different hormones and neurotransmitters are made from amino acids, noting where oxygen and/or metalloenzymes are used, and where in the cell the enzymes are active.

9. [Biochem] Investigate how zinc and magnesium are used for signaling, and compare and contrast to how calcium is used. Recently, a "zinc spark" was observed at fertilization, for example.

10. [Biochem] Investigate recent findings for how vision evolved. One recent finding to start with is PLoS One. 2015; 10(3): e0118415. doi: 10.1371/journal.pone.0118415 "Function and Evolutionary Origin of Unicellular Camera-Type Eye Structure"

11. [Biochem] Investigate the interplay between convergence and divergence in evolution at the level of biological species and phenotypes. Or, investigate a paper about evolutionary convergence or divergence at the molecular level.

Chapter 11: How Chemistry Shaped History

1. [Recap] What did this chapter have to say about “eusociality”? About what is different about the human brain? About the chemical rules that still constrain human society?

2. In Chapter 10, the chemistry of a neuron is presented, while in Chapter 11 the immense complexity of the human brain is presented. Although the chapter 11 concepts are built from many chapter 10 concepts, there are many things that appear in chapter 11 that never appeared before in Earth history. What are these things and why did they appear? Are you satisfied with the explanation that Chapter 11 concepts can emerge from Chapter 10 concepts, or is there something missing?

3. What does the arrow figure (Fig. 11.2, p.251) show? How is this arrow figure different from the previous arrow figures or chemical sequences discussed in the book?

4. What would happen if this chapter’s tape were rewound? Why might it be different from that of other chapters?

5. On p. 253, the idea is presented that larger and more complex mammalian species tend to be more vulnerable to extinction from environmental change. Look into this more and compare to old predators like sharks and alligators. Why do sharks and alligators persist if more complex species are more vulnerable to environmental change?

6. Is there a way in which human choices (like veganism) may be a source of artificial selection taking the place of natural selection, allowing us to evolve an augmented sense, or even a sixth sense (like the vampire bat), or to lose a sense (like the panda)? At what point would this result in a new species of human? Would this change what it means to be human? Why or why not?

7. [P-Chem] What is the connection between Energy Rate Density, internal complexity, and entropy?

8. [Biochem] Investigate how eusociality may evolve on the molecular level. Why are there eusocial insects and mammals, but not birds? Could dinosaurs have been eusocial?

9. [Biochem] Investigate the most recent hypotheses for why human brains are different. One interesting recent publication is Pontzer et al. Nature. 2016 May 4;533(7603):390-2. doi: 10.1038/nature17654. “Metabolic acceleration and the evolution of human brain size and life history.” Also see the TED talk "What is special in the human brain?" by Suzana Herculano-Houzel.

Chapter 12: A Familiar Refrain

1. What is the peak of evolutionary fitness? How would we know? Compare the fact that sensory organs operate near their limits (one photon) to the Lenski experiment that shows continual evolution.

2. Several movies and books have speculated on the future of human evolution: *WALL-E* and Neal Stephenson's *Seveneves*. What stories have you seen that involve this and what do they say about it? If lizards evolved in a decade, will humans evolve in 150? Why or why not?

3. Discuss the levels of predictability and freedom as you move through different "levels" of experience: quantum physics, chemical bonding in water, phase separations in chemistry, chirality of biomolecules such as amino acids, individual cells, tissues, organisms, social groups of organisms, the human brain, social groups of humans, the planet, and the galaxy. Too much predictability leads to determinism, while too much freedom leads to chaos. One author that would be interesting to engage on these issues would be Jared Diamond, especially his books *Guns, Germs, and Steel* and *Collapse.*

4. On p.264, the idea of "mistakes" in evolution is discussed. Discuss what kind of "mistakes" are truly mistakes and which have a degree of predictability. Is there a better word?

5. On p.265, the idea is presented that personal bias affects all scientific data to some degree. However, one cannot challenge every idea and has to accept many scientific data based on consensus. When it is worthwhile to revisit and challenge previous scientific discoveries and paradigms? The "Mismeasure of a Man" saga has continued in the pages of PLoS Biology: "Morton, Gould, and Bias: A Comment on "The Mismeasure of Science" by Michael Weisberg and Diane B. Paul (http://dx.doi.org/10.1371/journal.pbio.1002444).

6. [Biochem] How do you predict predictability in experimental evolution? What is the difference between evolutionary predictability and "Intelligent Design"?

Biochemistry Class Notes

A World from Dust was used in a Biochemistry Seminar course that followed completion of the typical undergraduate biochemistry sequence. (These activities can also be integrated into a traditional full-year biochemistry course.) The small size of this course and the fact that all students had completed study of the undergraduate textbook meant that the learning experience could be centered around in-depth presentations of peer-reviewed journal articles. Students were assigned to the first two presentations in pairs to teach teamwork and to allow time for all the presentations to fit into class time, but the last two presentations were solo, allowing students to learn presentation preparation tips from their partners before presenting by themselves in the second half of the course.

Four presentations were scheduled throughout the class that increased in complexity. Each presentation should be delivered after the students have the chance to read particular chapters in *A World from Dust*, as indicated:

1. **Protein Design** (aligns with AWfD Chapter 2): Students searched the literature for a recent protein design article and presented it to the rest of the class. This helps to introduce the students to literature searching because protein design is a well-delimited and focused area of study, and is relatively simple to find as a result. Also, protein design papers tend to have concrete, structural results that can be readily interpreted.
2. **Origin of Life** (aligns with AWfD Chapter 5): A file of recent origin-of-life papers (all containing experimental results in chemistry or biochemistry) was provided to the students. Each pair selected a paper and presented on it. This required limited literature searching to place the experiment in context. Each student was asked to cite which specific clue from Chapter 5 their experiment would fit under.
3. **Chemistry and Evolution** (aligns with AWfD Chapters 6-11): A file of recent papers involving a chemical hypothesis regarding evolution or history was provided to the students. Students were asked to present how the periodic table shaped that particular part of natural history and to find the chapter and sub-section in AWfD that describes that particular event or time. These papers generally required more literature searching to place into context than the Origin of Life papers.
4. **Evolution and Predictability** (aligns with AWfD chapter 12): Students searched the literature to find examples of either experimental evolution or historical investigation of evolution that spoke to levels of contingency and determinism – in other words, places where the Tape of Life was rewound and replayed, either by experiment or inference. Some possibilities are discussed in the text of Chapter 12, but students are encouraged to locate more recent developments by searching for recent papers that cite the papers referenced in Chapter 12. It's important to emphasize to the students that although the book is making an argument against radical contingency in evolution's history, that levels of contingency and divergence are fully expected – the question is to locate the levels at which convergence and divergence, and contingency and determinacy, operate.

Students were provided with evaluations for each presentation, giving specific encouragements and points for improvement. Also, for the final two presentations, students were asked to write three quiz questions and answers. The teacher selected (and in some cases modified) one of the three questions and gave the result to the class as a quiz to ensure active attention from all.

Origin of Life Presentations Bibliography (2016) (for biochem presentations)

Adamala, K. and J. W. Szostak (2013). "Competition between model protocells driven by an encapsulated catalyst." Nat Chem **5**(6): 495-501.

Adamala, K. and J. W. Szostak (2013). "Nonenzymatic Template-Directed RNA Synthesis Inside Model Protocells." Science **342**(6162): 1098-1100.

Barge, L. M., Y. Abedian, et al. (2015). "From Chemical Gardens to Fuel Cells: Generation of Electrical Potential and Current Across Self-Assembling Iron Mineral Membranes." Angewandte Chemie International Edition **54**(28): 8184-8187.

Boekhoven, J., W. E. Hendriksen, et al. (2015). "Transient assembly of active materials fueled by a chemical reaction." Science **349**(6252): 1075-1079.

Cafferty, B. J., I. Gállego, et al. (2013). "Efficient Self-Assembly in Water of Long Noncovalent Polymers by Nucleobase Analogues." Journal of the American Chemical Society **135**(7): 2447-2450.

Chen, M. C., B. J. Cafferty, et al. (2014). "Spontaneous Prebiotic Formation of a β-Ribofuranoside That Self-Assembles with a Complementary Heterocycle." Journal of the American Chemical Society **136**(15): 5640-5646.

Esselborn, J., C. Lambertz, et al. (2013). "Spontaneous activation of [FeFe]-hydrogenases by an inorganic [2Fe] active site mimic." Nat Chem Biol **9**(10): 607-609.

Roy, S. and A. K. Jones (2013). "Metalloenzymes: Cutting out the middleman." Nat Chem Biol **9**(10): 603-605.

Forsythe, J. G., S.-S. Yu, et al. (2015). "Ester-Mediated Amide Bond Formation Driven by Wet-Dry Cycles: A Possible Path to Polypeptides on the Prebiotic Earth." Angewandte Chemie International Edition **54**(34): 9871-9875.

Gopinath, P., V. Ramalingam, et al. (2015). "Magnesium pyrophosphates in enzyme mimics of nucleotide synthases and kinases and in their prebiotic chemistry." Proceedings of the National Academy of Sciences **112**(39): 12011-12014.

Heim, E. N., J. L. Marston, et al. (2015). "Biologically active LIL proteins built with minimal chemical diversity." Proceedings of the National Academy of Sciences **112**(34): E4717-E4725.

Hsiao, C., I. C. Chou, et al. (2013). "RNA with iron(II) as a cofactor catalyses electron transfer." Nat Chem **5**(6): 525-528.

Keller, M. A., A. Zylstra, et al. (2016). "Conditional iron and pH-dependent activity of a non-enzymatic glycolysis and pentose phosphate pathway." Science Advances **2**(1).

Li, L., C. Francklyn, et al. (2013). "Aminoacylating Urzymes Challenge the RNA World Hypothesis." Journal of Biological Chemistry **288**(37): 26856-26863.

(2013). "Casting Doubt on the RNA World Hypothesis : Aminoacylating Urzymes Challenge the RNA World Hypothesis." Journal of Biological Chemistry **288**(37): 26864-26864.

Longo, L. M., C. A. Tenorio, et al. (2015). "A single aromatic core mutation converts a designed “primitive” protein from halophile to mesophile folding." Protein Science **24**(1): 27-37.

Maga, G., G. Caetano-Anollés, et al. (2013). "Structural Phylogenomics Retrodicts the Origin of the Genetic Code and Uncovers the Evolutionary Impact of Protein Flexibility." PLoS ONE **8**(8): e72225.

Martinez-Rodriguez, L., O. Erdogan, et al. (2015). "Functional Class I and II Amino Acid-activating Enzymes Can Be Coded by Opposite Strands of the Same Gene." Journal of Biological Chemistry **290**(32): 19710-19725.

Mercier, R., Y. Kawai, et al. (2013). "Excess Membrane Synthesis Drives a Primitive Mode of Cell Proliferation." Cell **152**(5): 997-1007.

Koonin, Eugene V. and Armen Y. Mulkidjanian (2013). "Evolution of Cell Division: From Shear Mechanics to Complex Molecular Machineries." Cell **152**(5): 942-944.

Petrov, A. S., B. Gulen, et al. (2015). "History of the ribosome and the origin of translation." Proceedings of the National Academy of Sciences **112**(50): 15396-15401.

Saladino, R., E. Carota, et al. (2015). "Meteorite-catalyzed syntheses of nucleosides and of other prebiotic compounds from formamide under proton irradiation." Proceedings of the National Academy of Sciences **112**(21): E2746-E2755.

Ferus, M., A. Knížek, et al. (2015). "Meteorite-catalyzed synthesis of nucleosides and other prebiotic compounds." Proceedings of the National Academy of Sciences **112**(23): 7109-7110.

Sarkar, T., K. Selvakumar, et al. (2016). "Message in a molecule." Nat Commun **7**.

Stano, P., E. D'Aguanno, et al. (2013). "A Remarkable Self-Organization Process as the Origin of Primitive Functional Cells." Angewandte Chemie International Edition **52**(50): 13397-13400.

Toppozini, L., H. Dies, et al. (2013). "Adenosine Monophosphate Forms Ordered Arrays in Multilamellar Lipid Matrices: Insights into Assembly of Nucleic Acid for Primitive Life." PLoS ONE **8**(5): e62810.

Watanabe, H., K. Yamasaki, et al. (2014). "Tracing Primordial Protein Evolution through Structurally Guided Stepwise Segment Elongation." Journal of Biological Chemistry **289**(6): 3394-3404.

Chemistry and Evolution Presentations Bibliography 2016 (for biochem presentations)

Allen KD, Miller DV, Rauch BJ, Perona JJ and White RH (2015). Homocysteine Is Biosynthesized from Aspartate Semialdehyde and Hydrogen Sulfide in Methanogenic Archaea. Biochemistry *54*, 3129-3132.

Barb AW, Ho TG, Flanagan-Steet H and Prestegard JH (2012). Lanthanide binding and IgG affinity construct: Potential applications in solution NMR, MRI, and luminescence microscopy. Protein Science *21*, 1456-1466.

Bermejo-Deval R, Assary RS, Nikolla E, Moliner M, et al. (2012). Metalloenzyme-like catalyzed isomerizations of sugars by Lewis acid zeolites. Proceedings of the National Academy of Sciences *109*, 9727-9732.

Berndt A, Lee SY, Ramakrishnan C and Deisseroth K (2014). Structure-Guided Transformation of Channelrhodopsin into a Light-Activated Chloride Channel. Science *344*, 420-424.
Hayashi S (2014). Silencing Neurons with Light. Science *344*, 369-370.

Falta MT, Pinilla C, Mack DG, Tinega AN, et al. (2013). Identification of beryllium-dependent peptides recognized by CD4+T cells in chronic beryllium disease. The Journal of Experimental Medicine *210*, 1403-1418.

Foster AW, Osman D and Robinson NJ (2014). Metal Preferences and Metallation. Journal of Biological Chemistry *289*, 28095-28103.

Frick S, Nagel R, Schmidt A, Bodemann RR, et al. (2013). Metal ions control product specificity of isoprenyl diphosphate synthases in the insect terpenoid pathway. Proceedings of the National Academy of Sciences *110*, 4194-4199.

Gopinath P, Ramalingam V and Breslow R (2015). Magnesium pyrophosphates in enzyme mimics of nucleotide synthases and kinases and in their prebiotic chemistry. Proceedings of the National Academy of Sciences *112*, 12011-12014.

Gout E, Rébeillé F, Douce R and Bligny R (2014). Interplay of Mg2+, ADP, and ATP in the cytosol and mitochondria: Unravelling the role of Mg2+ in cell respiration. Proceedings of the National Academy of Sciences *111*, E4560-E4567.

Hultman J, Waldrop MP, Mackelprang R, David MM, et al. (2015). Multi-omics of permafrost, active layer and thermokarst bog soil microbiomes. Nature *521*, 208-212.

Irvine GW, Pinter TBJ and Stillman MJ (2016). Defining the metal binding pathways of human metallothionein 1a: balancing zinc availability and cadmium seclusion. Metallomics *8*, 71-81.

Kachroo AH, Laurent JM, Yellman CM, Meyer AG, et al. (2015). Systematic humanization of yeast genes reveals conserved functions and genetic modularity. Science *348*, 921-925.

Knape MJ, Ahuja LG, Bertinetti D, Burghardt NCG, et al. (2015). Divalent Metal Ions Mg2+and Ca2+Have Distinct Effects on Protein Kinase A Activity and Regulation. ACS Chemical Biology *10*, 2303-2315.

Lisi GP, Png CYM and Wilcox DE (2014). Thermodynamic Contributions to the Stability of the Insulin Hexamer. Biochemistry *53*, 3576-3584.

Maloof JN, Chao D-Y, Chen Y, Chen J, et al. (2014). Genome-wide Association Mapping Identifies a New Arsenate Reductase Enzyme Critical for Limiting Arsenic Accumulation in Plants. PLoS Biology *12*, e1002009.

Meadows R (2014). How Plants Control Arsenic Accumulation. PLoS Biol *12*, e1002008.

Pan T-CF, Applebaum SL and Manahan DT (2015). Experimental ocean acidification alters the allocation of metabolic energy. Proceedings of the National Academy of Sciences *112*, 4696-4701.

Parmar AS, Xu F, Pike DH, Belure SV, et al. (2015). Metal Stabilization of Collagen and de Novo Designed Mimetic Peptides. Biochemistry *54*, 4987-4997.

Poulain AJ, Aris-Brosou S, Blais JM, Brazeau M, et al. (2015). Microbial DNA records historical delivery of anthropogenic mercury. The ISME Journal *9*, 2541-2550.

Sato A, Nagasaka S, Furihata K, Nagata S, et al. (2011). Glycolytic intermediates induce amorphous calcium carbonate formation in crustaceans. Nat Chem Biol *7*, 197-199.

Weiss IM (2011). Biomaterials: Metabolites empowering minerals. Nature Chemical Biology *7*, 192-193.

Senatore A, Guan W, Boone AN and Spafford JD (2014). T-type Channels Become Highly Permeable to Sodium Ions Using an Alternative Extracellular Turret Region (S5-P) Outside the Selectivity Filter. Journal of Biological Chemistry *289*, 11952-11969.

Shields-Cutler RR, Crowley JR, Hung CS, Stapleton AE, et al. (2015). Human Urinary Composition Controls Antibacterial Activity of Siderocalin. Journal of Biological Chemistry *290*, 15949-15960.

(2015). Urine pH and Composition Influence the Potency of a Human Antimicrobial Molecule During Urinary Tract Infections: Human Urinary Composition Controls Antibacterial Activity of Siderocalin. Journal of Biological Chemistry *290*, 15961.

Teder T, Lõhelaid H, Boeglin WE, Calcutt WM, et al. (2015). A Catalase-related Hemoprotein in Coral Is Specialized for Synthesis of Short-chain Aldehydes. Journal of Biological Chemistry *290*, 19823-19832.

Timucin E and Sezerman OU (2015). Zinc Modulates Self-Assembly ofBacillus thermocatenulatusLipase. Biochemistry *54*, 3901-3910.

Tolmacheva AS, Blinova EA, Ermakov EA, Buneva VN, et al. (2015). IgG abzymes with peroxidase and oxidoreductase activities from the sera of healthy humans. Journal of Molecular Recognition *28*, 565-580.

Winzer T, Kern M, King AJ, Larson TR, et al. (2015). Morphinan biosynthesis in opium poppy requires a P450-oxidoreductase fusion protein. Science *349*, 309-312.

Zeng G, Zhang R, Xuan W, Wang W and Liang F-S (2015). Constructingde NovoH2O2Signaling via Induced Protein Proximity. ACS Chemical Biology *10*, 1404-1410.

Zhou X, Cooper KL, Sun X, Liu KJ and Hudson LG (2015). Selective Sensitization of Zinc Finger Protein Oxidation by Reactive Oxygen Species through Arsenic Binding. Journal of Biological Chemistry *290*, 18361-18369.

Physical Chemistry Class Notes

A World from Dust aligns with the typical sequence of topics in physical chemistry courses. The course I have specifically aligned is a Survey of Physical Chemistry course using Atkins and de Paula's *Physical Chemistry for the Life Sciences*, but most books follow a similar sequence that can be aligned with the narrative in AWfD.

Topic	Time (BYa)	A World from Dust Chapters	Atkins PCftLS Chapters
Entropy	~13	Ch.3 = After Big Bang: Universe cools	Ch.1&2 = Cooling upon expansion
Enthalpy	~4.5	Ch.4 = Hadean Earth: Al, Mg bind O more than S	Ch.1&2 = Heats of formation (oxides v. sulfides)
Phase diagrams	~4.5	Ch.4 = Fe phase diagrams explain Earth's solid core	Ch.3 = Phase diagrams of water and mixtures
Solubility equilibria	~4	Ch.4 = Ksp explains which elements are available in the sea for life	Ch.4 = Ksp calculations
Binding equilibria	~3.7	Ch.6 = After origin of life: Irving-Williams series sets cytoplasmic metal concs.	Ch.4 = K for binding interactions
Redox potentials	~1	Ch.8 = Oxidation changed redox-sensitive elements by E	Ch.5 = E calculations
Kinetics	~0.6	Ch.10 = Na+ and K+ were fast ions selected for fast neural signals	Ch.6&7 = k calculations and comparisons

Class Organization: Eight chapters of Atkins and de Paula we covered. Two chapters of Atkins correspond to three chapters of *A World from Dust*, so after each pair of Atkins chapters, I presented a "Data Talk" which connected the physical chemistry concepts from Atkins with the chemical concepts in the narrative of natural history as told in *AWfD*. Each of these "Data Talks" included figures and/or tables of physical chemistry data that supported some of the points in the natural history narrative. Also, some stories from journal articles (with text from the article) were integrated into the Data Talk to help teach how to read a journal article. At the end of the course, a final presentation was assigned in which the students chose an element from the narrative of *AWfD* and presented its role in natural history and its chemical properties, so that they learned literature searches and science communication.

Atkins *Physical Chem for Life Sci* Chapters	***A World from Dust* Chapters**	**Data Talk Topics**
1 (Enthalpy) 2 (Entropy)	1 (Environment) 2 (Chemistry & Biology) 3 (Periodic Table)	PCA analysis to re-create the Periodic Table Irving-Williams series and binding Why did the Universe cool? = Configurational entropy
3 (Phase Diagrams) 4 (Equilibria)	4 (Liquid oceans) 5 (Origin of life) 6 (Anoxic biochemistry)	Why is fire always hot? Harvesting IR from Earth The Great Nickel Famine
5 (Electrochem) 6 (Kinetics)	7 (Colors of photosynthesis) 8 (The Great Oxidation Event) 9 (The Cambrian Explosion)	How meteorites catalyze hydrogen Mn's catalytic personality David and Alm's data backing up the Arrow through the Ocean Redox potentials and life
7 (Kinetic mech.) 11 (Modeling)	10 (Fast signals and brains) 11 (Human brain and society) 12 (Experimental evolution)	Organs and organelles Kinetics of different elements Kinetic mechanism of Pepto-Bismol (returns to AWfD Ch.2 in detail)

Many of the topics above are associated with particular journal articles cited in the individual Data Talks, and these may be assigned to students in year-long physical chemistry courses so that they can learn directly from the literature.

Data Talk 1 = AWfD Chapters 1-3 = Atkins Chapters 1-2

Boylan-Kolchin, M. (2014). "Cosmology: A virtual Universe." Nature **509**(7499): 170-171.

Besalú, E. (2013). "From Periodic Properties to a Periodic Table Arrangement." Journal of Chemical Education **90**(8): 1009-1013.

Hunter, T. (2012). "Why nature chose phosphate to modify proteins." Philosophical Transactions of the Royal Society B: Biological Sciences **367**(1602): 2513-2516.

Langbeheim, E., S. A. Safran, et al. (2014). "Visualizing the Entropy Change of a Thermal Reservoir." Journal of Chemical Education **91**(3): 380-385.

Bloch, E. D., M. R. Hudson, et al. (2014). "Reversible CO Binding Enables Tunable CO/$H_2$and CO/N_2Separations in Metal–Organic Frameworks with Exposed Divalent Metal Cations." Journal of the American Chemical Society **136**(30): 10752-10761.

Data Talk 2 = AWfD Chapters 4-6 = Atkins Chapters 3-4

Park, T., J. Na, et al. (2015). "Photothermally Activated Pyroelectric Polymer Films for Harvesting of Solar Heat with a Hybrid Energy Cell Structure." ACS Nano **9**(12): 11830-11839.

Schmidt-Rohr, K. (2015). "Why Combustions Are Always Exothermic, Yielding About 418 kJ per Mole of O_2." Journal of Chemical Education **92**(12): 2094-2099.

Data Talk 3 = AWfD Chapters 7-9 = Atkins Chapters 5-6

Gao, J., Y. Zheng, et al. (2015). "Identification of molybdenum oxide nanostructures on zeolites for natural gas conversion." Science **348**(6235): 686-690.

Navarro-Ruiz, J., P. Ugliengo, et al. (2016). "Does Fe^{2+}in olivine-based interstellar grains play any role in the formation of H_2? Atomistic insights from DFT periodic simulations." Chem. Commun. **52**(42): 6873-6876.

Zhang, C., C. Chen, et al. (2015). "A synthetic Mn_4Ca-cluster mimicking the oxygen-evolving center of photosynthesis." Science **348**(6235): 690-693.

Romero-Canelón, I. and P. J. Sadler (2015). "Systems approach to metal-based pharmacology: Fig. 1." Proceedings of the National Academy of Sciences **112**(14): 4187-4188.

Data Talk 4 = AWfD Chapters 10-12 = Atkins Chapters 7, 11

Hong, Y., Y.-T. Lai, et al. (2015). "Glutathione and multidrug resistance protein transporter mediate a self-propelled disposal of bismuth in human cells." Proceedings of the National Academy of Sciences **112**(11): 3211-3216.

Simon, D. T., K. C. Larsson, et al. (2015). "An organic electronic biomimetic neuron enables auto-regulated neuromodulation." Biosensors and Bioelectronics **71**: 359-364.

Stockbridge, R. B. and R. Wolfenden (2011). "Enhancement of the Rate of Pyrophosphate Hydrolysis by Nonenzymatic Catalysts and by Inorganic Pyrophosphatase." Journal of Biological Chemistry **286**(21): 18538-18546.

Zhang, X. C. and L. Han (2016). "How does the chemical potential of the substrate drive a uniporter?" Protein Science **25**(4): 933-937.

First-year Class Notes

This book is targeted toward upper-division students, and so lower-division students will have questions about how the content fits together, and the discussion should start with that. For each chapter, the teacher can ask about which you have and haven't discussed in previous classes, and ask which topics you have questions about.

First can talk about the periodic table. What does it tell you? How have you used it? Then, ask students to redefine certain terms in their own words, for each chapter:

1. DNA, acids and bases, lake chemistry, how proteins work, phosphate, magnesium, enzymes, "Tape of Life."

2. The Central Dogma of DNA → mRNA → Proteins, sulfur, reactive oxygen species (ROS), antioxidants, iron in blood, zinc in designed proteins, the Accidental Enzyme.

3. The periodic table, electron orbitals, stars making elements, the Big Six elements, the moon.

4. Other possible places for life in the solar system, combustion, Arrow Through the Sky, plate tectonics, water, dissolving.

5. List the seven clues and say something about each one, iron and sulfur working together.

6. Nickel, tungsten, cobalt, Winogradsky column, wheels of reactions, methanophages/ methanogens, the Great Nickel Famine

7. Manganese, pigments, plastids, mitochondria, different colored places, what different colors did you see in this chapter?

8. Molybdenum, copper, and zinc, the Great Oxygenation Event, the Arrow Through the Ocean, oxygen as a "double-edged sword," nitrogen fixation.

9. Calcium, the Cambrian Explosion, the Great Unconformity, external structures formed by sugars and calcium, alginate.

10. Sodium, potassium, and chloride, how do brains work?, the five senses, extinction, convergence.

11. Eusociality, the human brain, Energy Rate Density, Arrow Through History (of mining) human society and chemistry.

12. The "Tape of Life," experimental evolution, art, mistakes and science reporting.