What is life?

Jonathan Birch
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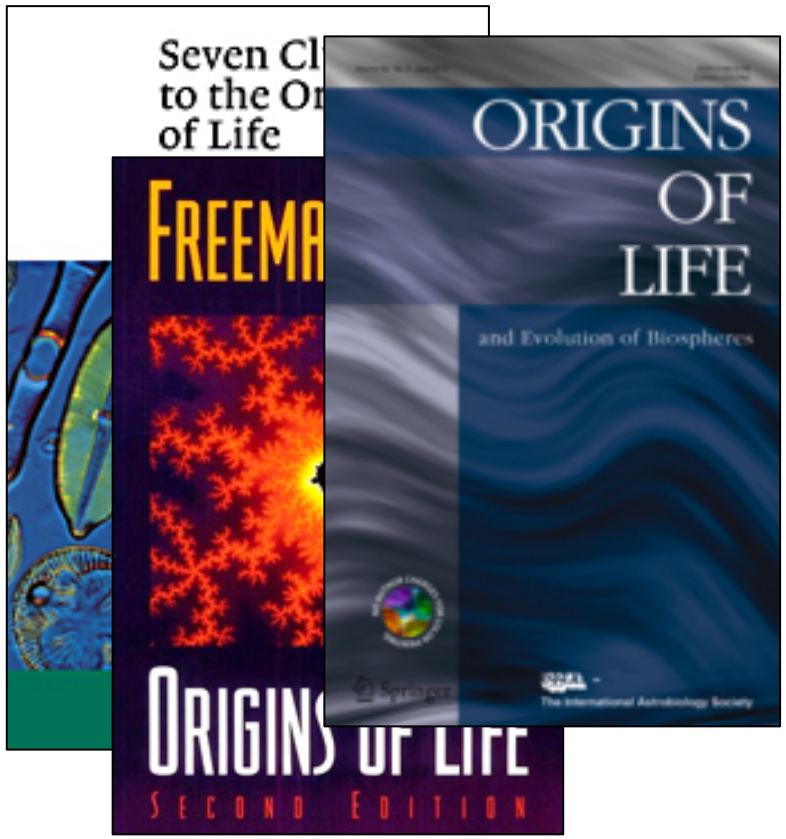
I Who cares?

Four research programmes for which the nature of life is a matter of on-going concern:

- Origins of life
- Astrobiology / exobiology
- Artificial life / 'A-Life'
- Synthetic biology / xenobiology



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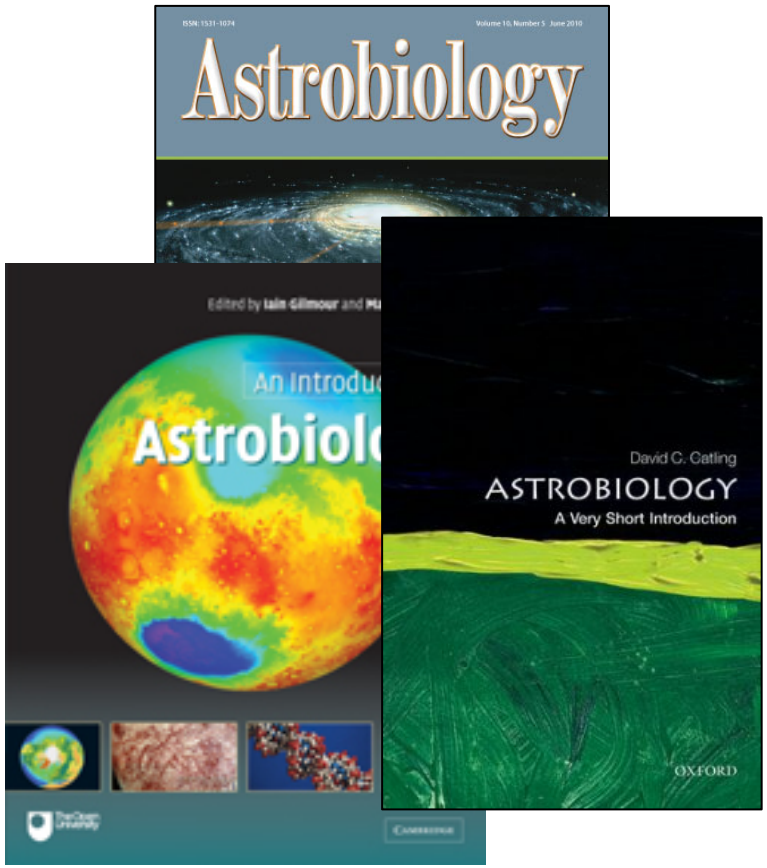

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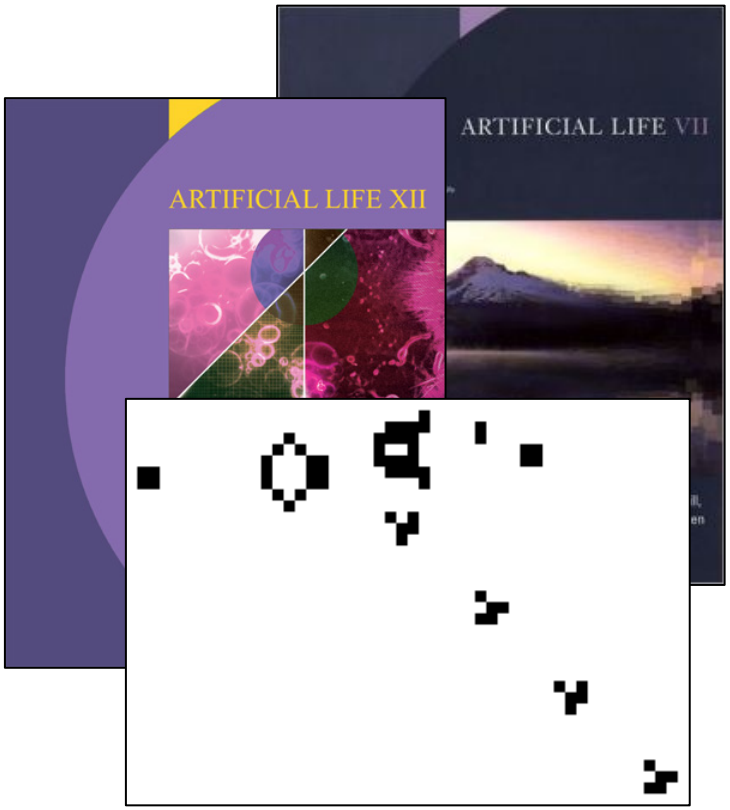

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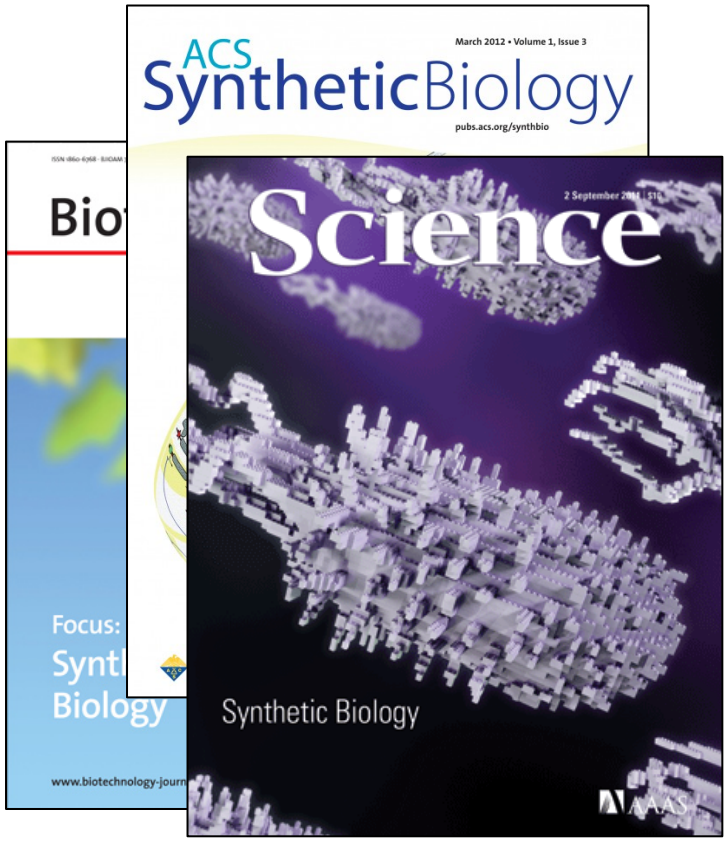

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- [illegible]
- [illegible]
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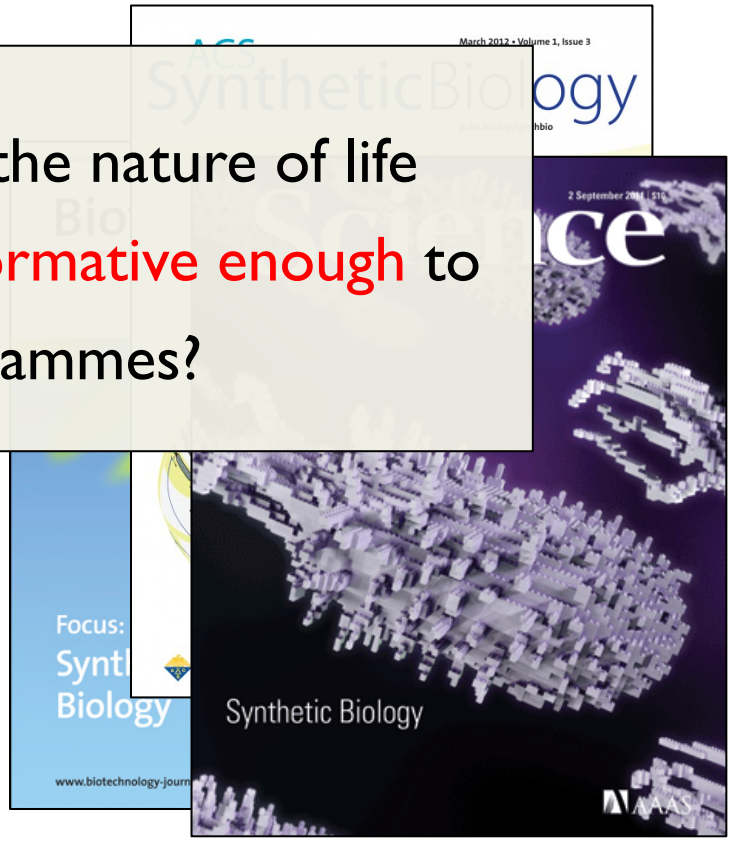
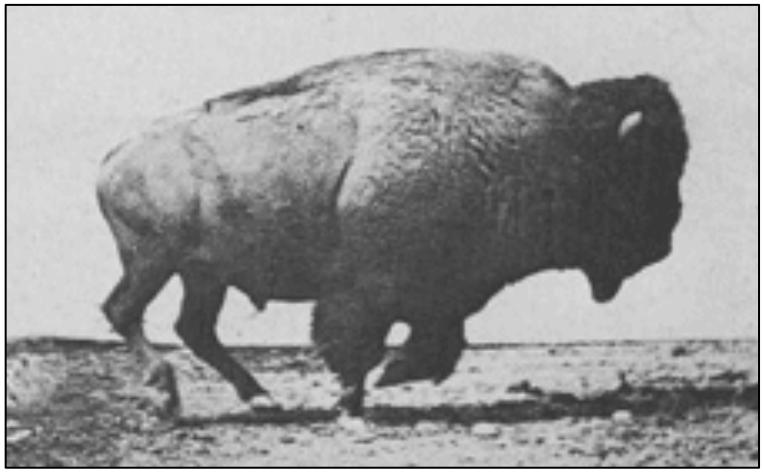
Q: Can we give an account of the nature of life that is general enough and informative enough to meet the needs of these programmes?



2 Signs of life

A traditional physiological checklist:

- Movement
- Respiration
- Response to Stimuli
- Growth
- Reproduction
- Excretion
- Nutrition



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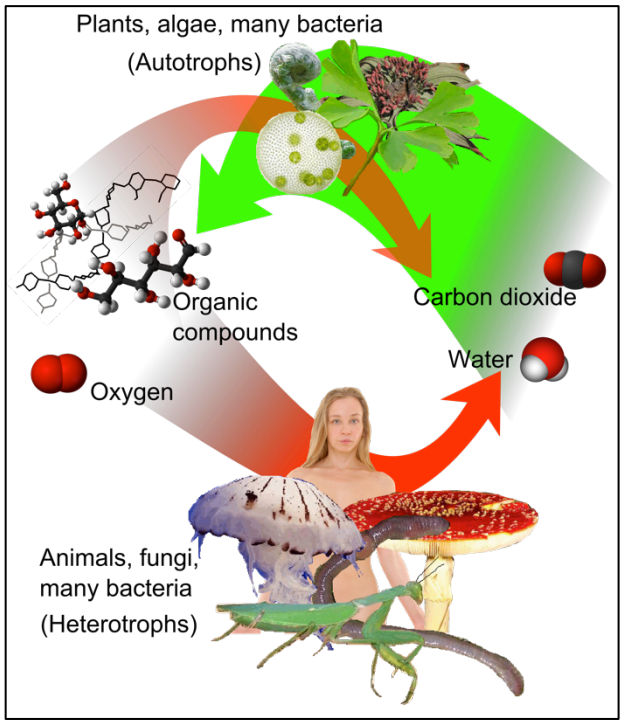

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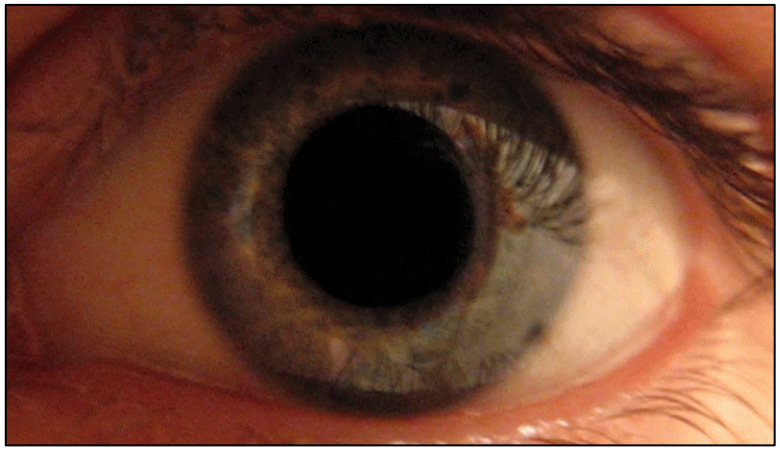

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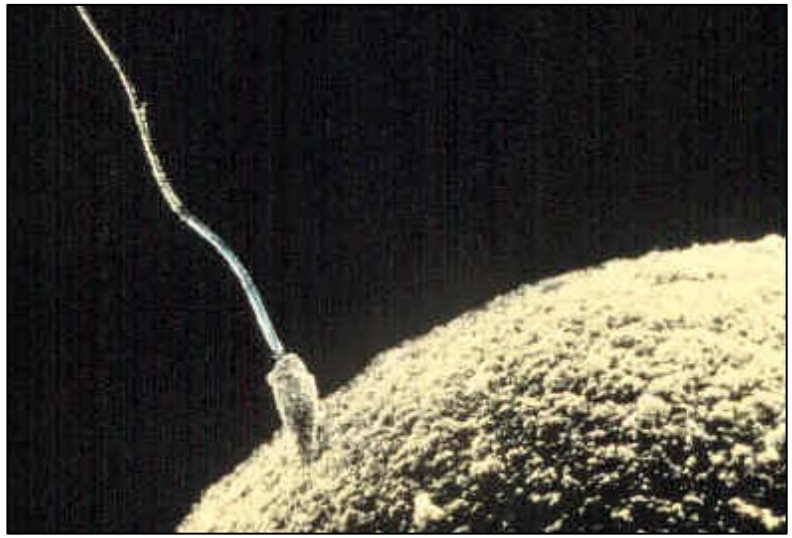

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2 Signs of life

Some problems with these checklists:

- Many non-living systems satisfy at least one (and sometimes nearly all) of the criteria.

2 Signs of life

Some problem

- Many (usually all) of the

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A car moves, responds to stimuli, takes in fuel from the environment, oxidizes organic compounds, and excretes waste products (5/7).

2 Signs of life

Some problems

- Many nonliving things exhibit (some of) the

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A forest fire moves, grows, takes in fuel, oxidizes organic compounds, 'excretes' smoke, and 'reproduces' through spark dispersal (6/7).

2 Signs of life

Some problems with these checklists:

- Many non-living systems satisfy at least one (and sometimes nearly all) of the criteria.
- Many living systems fail to satisfy at least one of the criteria.

2 Signs of life

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A mule cannot reproduce (6/7). A comatose geriatric mule cannot reproduce, respond to stimuli or grow (4/7).

2 Signs of life

Some problems with these checklists:

- Many non-living systems satisfy at least one (and sometimes nearly all) of the criteria.
- Many living systems fail to satisfy at least one of the criteria.
- The criteria are highly disparate. Why do these processes occur together, and why does something special result when they do?

→ Physiological checklists provide fairly reliable diagnostic criteria for life in ordinary contexts, but they do not capture the fundamental nature of the phenomenon.

3 The '*n* = 1' problem

A natural thought:

Surely the solution is to 'go molecular'. If we want to understand the fundamental nature of life, we need to look at the cellular processes that sustain it.

But…

Sagan 1974, Cleland and Chyba 2002: All present-day life on Earth is descended from a single common ancestor. This makes it extremely difficult to tell which processes are essential to life and which are historically contingent features of present-day life on Earth.

3 The '*n* = 1' problem

For example…

- DNA

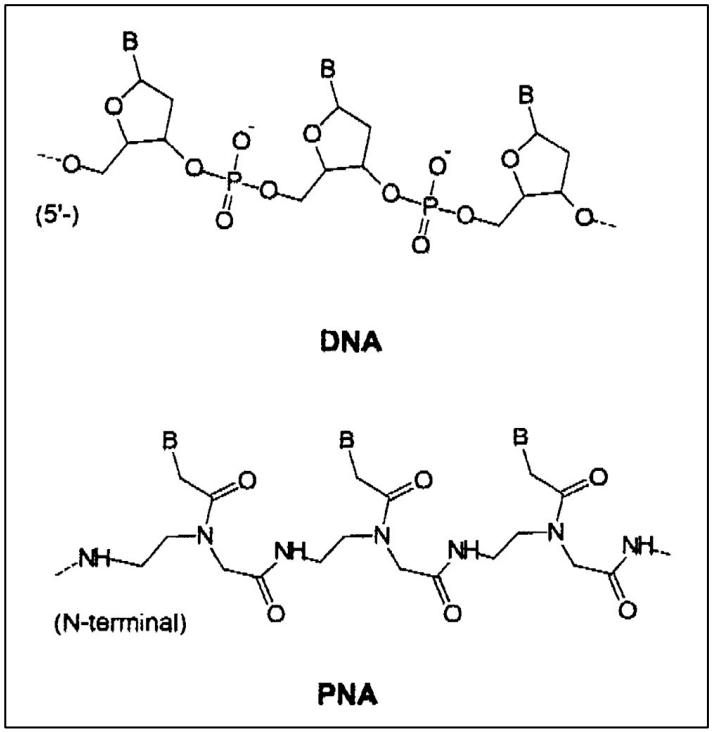
  Essential or historically contingent?

- Carbon

  Essential or historically contingent?

- Water

  Essential or historically contingent?



Public domain image from the Nielsen et al. PNA patent (2000)

Pinheiro et al. (2012) Synthetic genetic polymers capable of heredity and evolution. *Science* 336: 341-344

Wolfe-Simon et al. (2010) A bacterium that can grow by using arsenic instead of phosphorus. *Science* 332: 1163-1166 [see also ensuing controversy!]

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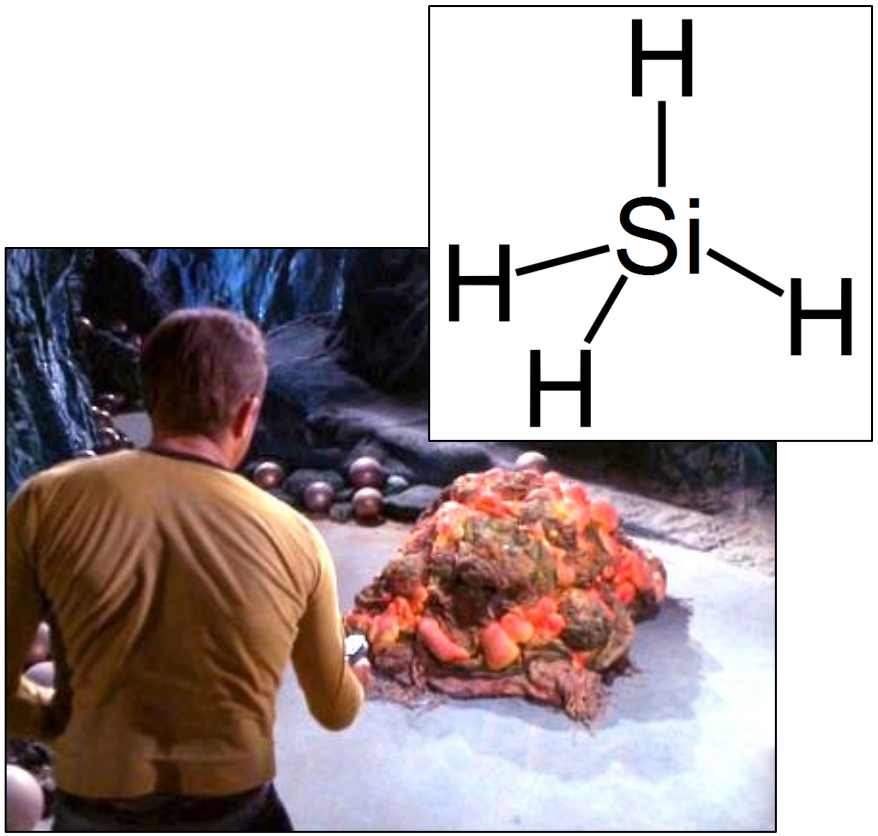

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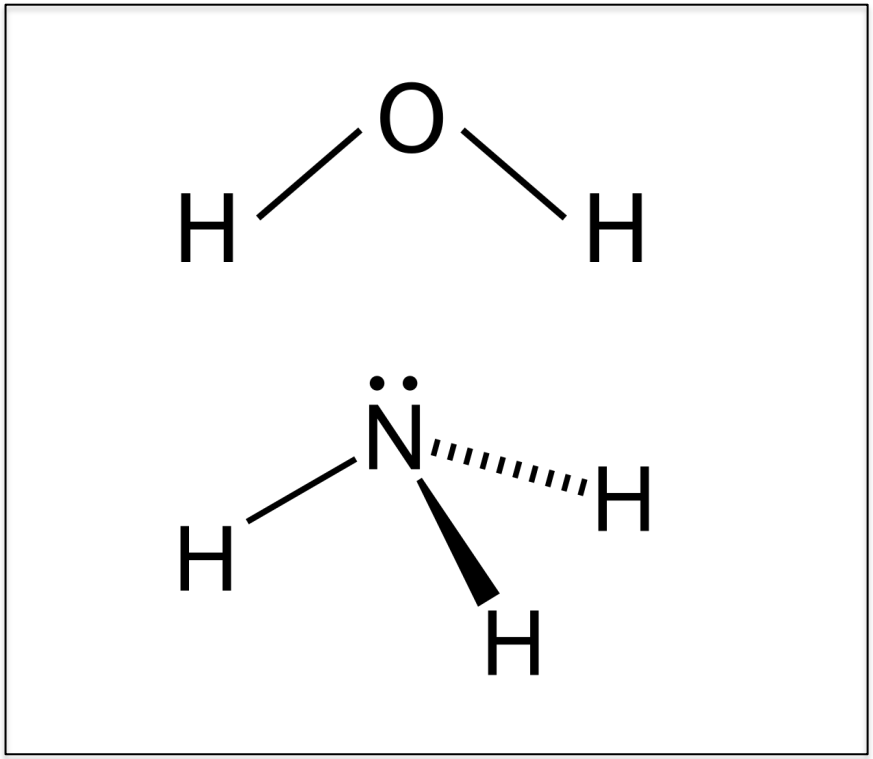

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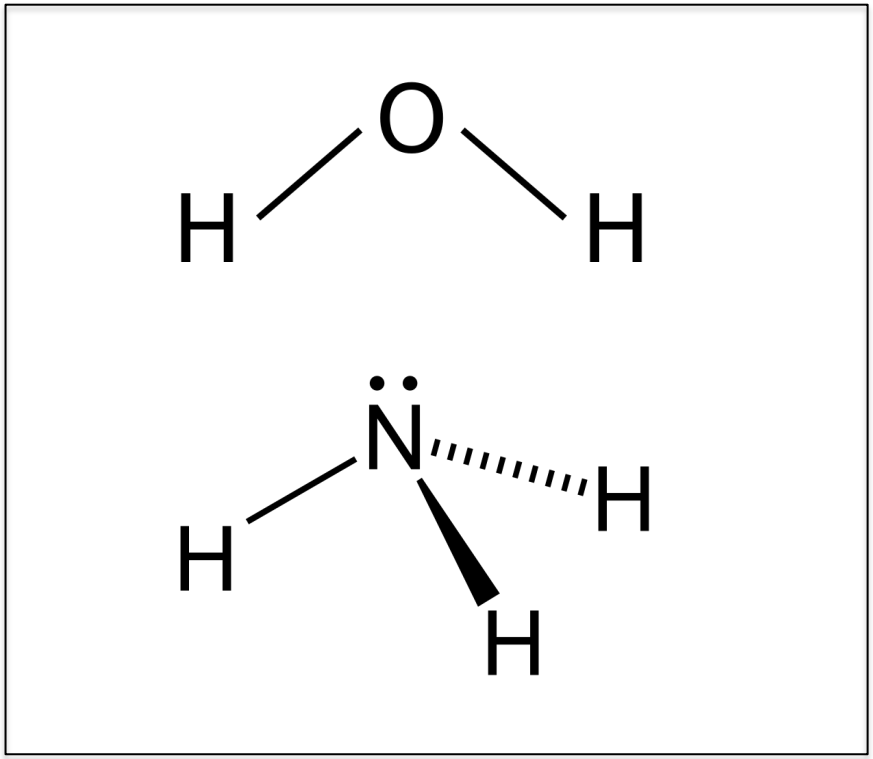

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Even when we can rule out hypothesized alternatives, unconceived alternatives remain a concern.

3 The '*n* = 1' problem

Cleland and Chyba 2002:

"It is a bit like trying to come up with a theory of mammals when one can observe only zebras. What features of zebras should one focus upon—their stripes, common to all, or their mammary glands, characteristic only of the females? In fact, the mammary glands, although present in only some zebras, tell us more about what it means to be a mammal than do the ubiquitous stripes. Without access to living things having a different historical origin, it is difficult and perhaps ultimately impossible to formulate an adequately general theory of the nature of living systems."

3 The '*n* = 1' problem

Sagan 1974:

"There is no aspect of contemporary biology in which we can distinguish the evolutionary accident from the biological *sine qua non*. We cannot distinguish the contingent from the necessary. The time scale of the evolutionary process is so long that it is unlikely that such questions will ever be answered by terrestrial experimentation. For this reason biology suffers from a deadening provincialism, an inevitable parochialism - like the physics of falling bodies before Newton showed that the same laws applied to the motion of apples in England, the moon in circumterrestrial space and the planets about the Sun. The deparochialization of biology can only come in the same way: by comparisons with examples elsewhere, by the pursuit of extraterrestrial life."

…but in order to identify 'examples elsewhere', don't we need some idea of what it is we're looking for?

4 The NASA 'working definition'

> Life is a self-sustained chemical system capable of undergoing Darwinian evolution.

'Capable of undergoing Darwinian evolution'?

Joyce: Darwinian evolution "has an associated property list: you can't have Darwinian evolution without self-replication or reproduction. You can't have it without mutability, heritability, and variation of form and function. And metabolism is in there too."

- Though this resembles traditional physiological checklists, its emphasis is very different.
- Mutability, heritability and variation (variability) are properties of traits or lineages of traits, not properties of individual organisms.

4 The NASA 'working definition'

> Life is a self-sustained chemical system capable of undergoing Darwinian evolution.

'Self-sustained'?

Joyce: this means that "all of the information necessary for the system to undergo Darwinian evolution must be part of the system".

e.g. On Earth, all living things contain DNA, and Darwinian evolution proceeds through gradual alteration of DNA sequences.

→ Intended to exclude viruses (they rely on the cellular machinery of a host cell, but do not contain the information necessary to reproduce that machinery).

4 The NASA 'working definition'

> Life is a self-sustained chemical system capable of undergoing Darwinian evolution.

Some concerns:

- Darwinian evolution happens to populations or lineages (typically over long timescales), not to individual living things.

  → An individual living thing = any entity that belongs to some such population or lineage (and meets the 'self-sustained' criterion).

- Does life have to be chemically realized?

  → Joyce's pragmatic/flippant response: "NASA's not expecting to find a bunch of supercomputers on Mars or Titan. Or even PCs or iPhones."

- Is Darwinian evolution the only game in town?

  → The notions of 'adaptive evolution' or 'open-ended evolution' are more general, and might do the job. But they are also less informative.

4 The NASA 'working definition'

An unsolved problem

It has proved extremely difficult to construct a characterization of life that is both:

- Sufficiently general to cover all possible cases, without geocentric parochialism.
- Sufficiently informative to meet the needs of the biologists for whom it matters.

'One line' definitions are insufficiently informative. We need to flesh them out with concrete biological detail. But as soon as we try to do that, we run straight into the '*n* = 1' problem.

5 Summary

- The nature of life is an old chestnut that remains a contested issue among researchers interested in the origin of life, artificial life, synthetic life or extraterrestrial life.
- Traditional physiological checklists are not useless, but they do not meet the needs of these fields.
- Biochemical definitions of life suffer from the '$n = 1$' problem. Because all life on Earth has a single common ancestor, we are trying to generalize from a single case, unable to distinguish essential properties from historical accidents.
- The NASA 'working definition' is that 'life is a self-sustained chemical system capable of undergoing Darwinian evolution'.
- This exemplifies many of the problems that 'definitions of life' tend to face. By adding detail to make the definition informative, we run the risk of those details being mere historical contingencies.