

Universal Constraints - An Astrobiological Perspective on Life

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The background of the slide is a composite image. On the left, a portion of the Earth is visible from space, showing the blue oceans and brown/green landmasses. On the right, a vibrant, multi-colored galaxy (possibly the Orion constellation) is visible against a dark, star-filled sky. The overall color palette is dominated by blues, greens, and purples.

Astrobiology

Origin, evolution, and distribution of life in the universe.^{1,2}

Does life exist elsewhere?

What rules, patterns and limits (of chemistry, biology and kinesiology) are universal, regardless of where life emerges?^{1,2}

Chemistry Lens

231.654

What chemical rules and patterns are universal, regardless of where life emerges?

Are the chemical systems that we know and somewhat understand, universal? Is Earth unique?

If there is life out there, how can we confirm it using chemistry?

Chemistry is the building blocks of life.

Universal chemical requirements for life

3 essential requirements:^{2,3}

1. A solvent
2. Stability and reactivity
3. Diversity



Figure 3: Generic liquid.

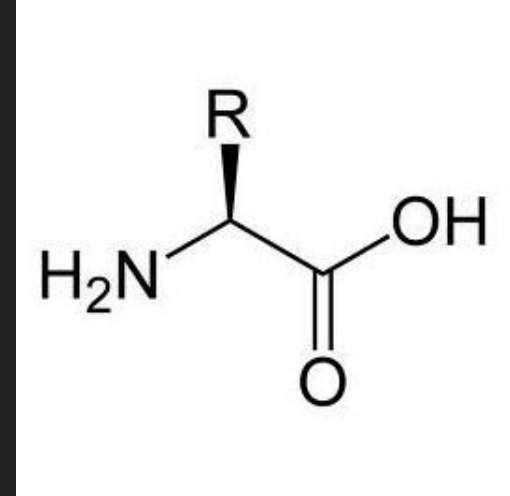


Figure 4: Amino acid.

Solvent

- Water = 2nd most abundant molecule in the universe.¹
- Superior properties.³
- High cohesion, high heat capacity, high dielectric constant.³
- Water = Universal chemical constraint for life. (Probably)

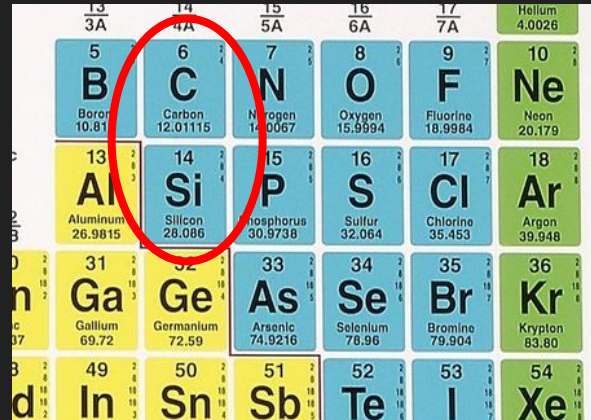
Backbone for life - Carbon vs. Silicon^{4,5}

Universal restraints:

Diverse?

Stable and reactive?

Compatible with solvent?



| | | | | | |
|---------------------------------|--------------------------------|----------------------------------|-------------------------------|--------------------------------|------------------------------|
| 5 B Boron 10.81 | 6 C Carbon 12.01115 | 7 N Nitrogen 14.0067 | 8 O Oxygen 15.9994 | 9 F Fluorine 18.9984 | 10 Ne Neon 20.179 |
| 13 Al Aluminum 26.9815 | 14 Si Silicon 28.086 | 15 P Phosphorus 30.9738 | 16 S Sulfur 32.064 | 17 Cl Chlorine 35.453 | 18 Ar Argon 39.948 |
| 31 Ga Gallium 69.72 | 32 Ge Germanium 72.59 | 33 As Arsenic 74.9216 | 34 Se Selenium 78.96 | 35 Br Bromine 79.904 | 36 Kr Krypton 83.80 |

[Stock image of periodic table]

Silicon fails, Carbon passes with flying colours.^{4,5}



Figure 6: Artists rendition of organo-silicon based life.



What are the universal chemical requirements?

- a) Diversity, reactivity, stability
- b) Truth, love, kindness
- c) Diversity, reactivity and stability, a solvent
- d) Water, Silicon, Carbon dioxide

Prebiotic chemistry^{6,7}

What we don't know:^{6,7}

- Timing.
- Surface & atmospheric conditions.
- Availability of organics.

What we do know:^{6,7}

- Possible environments.
- Sources of organic matter.



Figure 7: Artist's image of prebiotic Earth.

Biosignatures: Fingerprints of life⁸

IF life has been kickstarted on an exoplanet, how can we know?

Molecular patterns indicating biological activity.⁸

- Distributions
- Disequilibrium
- Complex organics

Challenges:⁸

- Atmosphere dilutes signals.
- Abiotic processes can give false +ve's.



Figure 8: Spock searching for signs of life.

Technosignatures: Fingerprints of “intelligent” life^{9,10}

Observational indications of technology.

Modifications to planets atmosphere or surface not explained by natural processes.^{9,10}

- Tritium
- CFC's

Low false +ve's, ability to detect.¹⁰



Figure 9: Industrial air pollution.

The Biological Bottleneck

- Chemistry is Common; Biology is Complex.
- Amino acids and organic molecules are found on meteorites and comets.¹¹
- The transition from non-living chemistry to a self-replicating organism (Abiogenesis) is the first major hurdle.¹²

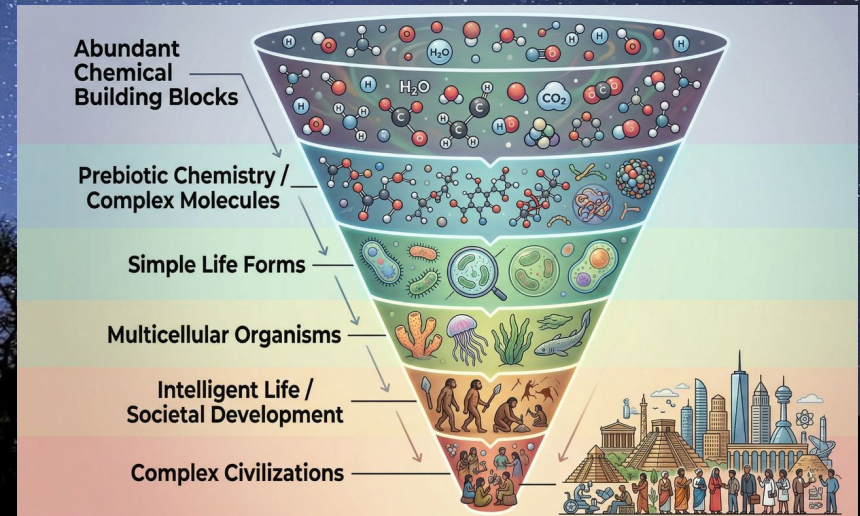


Figure 10: Cosmic Evolution Funnel

Which developmental step do you think is the hardest for life to overcome?

- **A) Abiogenesis:** Getting nonliving chemicals to form a living cell.
- **B) Multicellularity:** Single cells learning to cooperate as a complex organism.
- **C) Intelligence:** Evolving a brain capable of logic and tool use.
- **D) Technological Survival:** Surviving the invention of nuclear weapons, A.I., etc.

Convergent Evolution (A Universal Algorithm)

- **Nature Repeats Its Best Ideas.**
- **Convergent Evolution:** Unrelated organisms evolve similar traits to solve the same environmental problems.¹⁵
 - o Ex: Eyes, wings, echolocation, and hydrodynamic body shapes
- Alien life will likely possess recognizable sensory organs and appendages optimized for their specific environment.

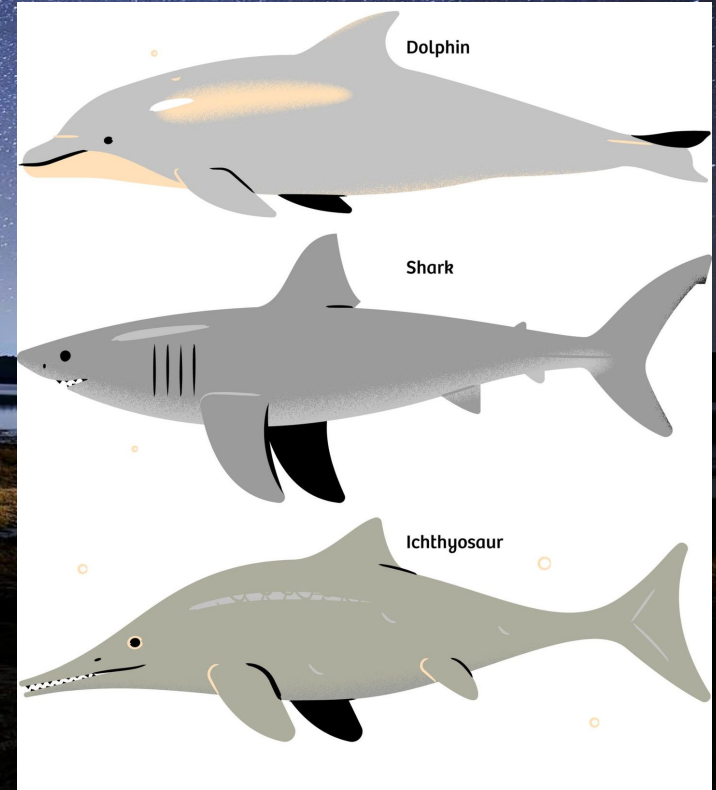


Figure 12 : Convergent Evo. Example

The M-Dwarf Dilemma

- M-class stars make up ~75% of our galaxy.¹⁶
- To have liquid water, a planet must orbit incredibly close to a dim M-Star.¹⁷
- This tight orbit causes the planet to lock. One side always faces the star (permanent day), the other faces deep space (permanent night).¹⁷

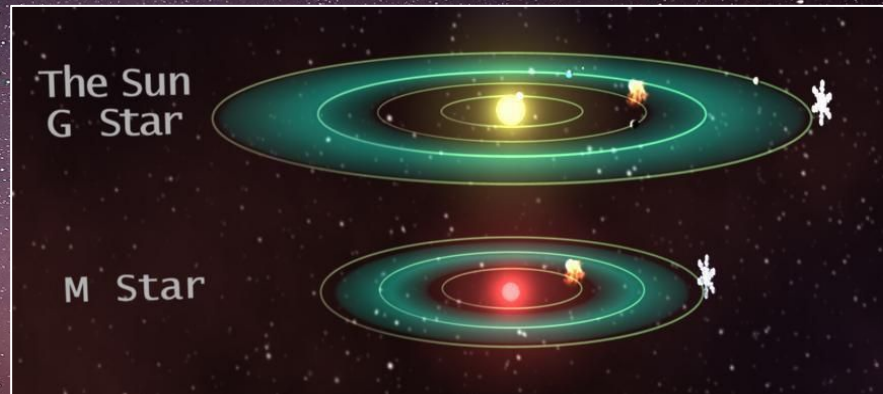


Figure 13 : Habitable Zones of G and M class stars

Biology of a Tidally Locked World

- **The Terminator Zone:** The only survivable strip is the twilight ring between day and night.¹⁸
- **Biological Adaptations:**
 - **No Circadian Rhythms:** No day/night cycle means sleep patterns would evolve completely differently.
 - **Sensory Shifts:** M-Stars emit heavily in the infrared. Alien eyes would evolve to see heat rather than visible light.
 - **Extreme Flora:** Plants would likely be black to absorb as much of the dim infrared light as possible.¹⁹



Figure 14: Illustration of a Tidally Locked Planet

Biology's Limit is Physics

- **Biology is highly adaptable, but it cannot break the laws of physics.**
- As organisms grow in size, environmental mechanics (gravity, atmospheric pressure) take control of their evolution.²⁰

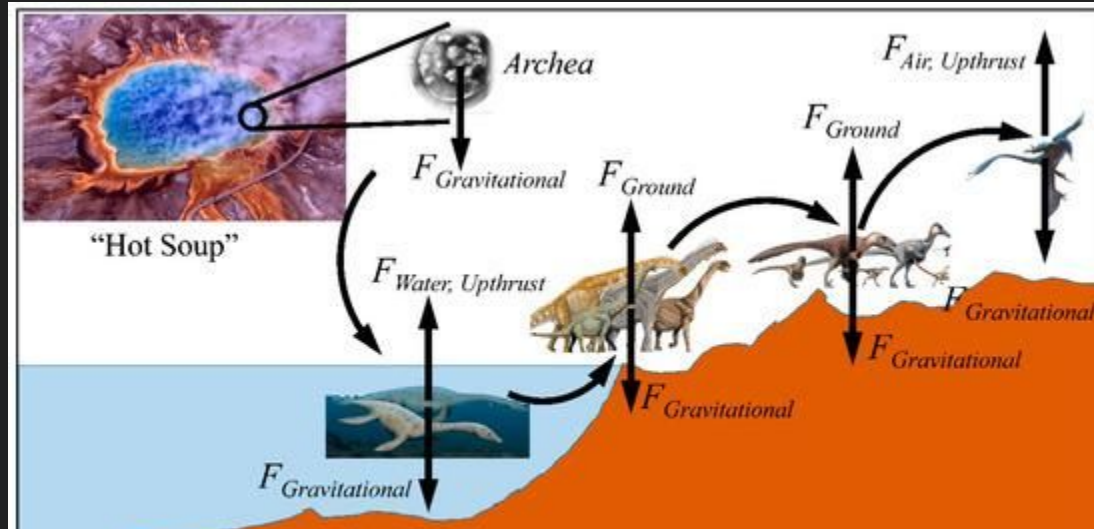


Figure 15: Force of gravity acting on all stages of evolving life.

Gravity is a Body Design Problem

Earth = 1 g²¹



Figure 16: Earth

Titan = 0.138 g²²

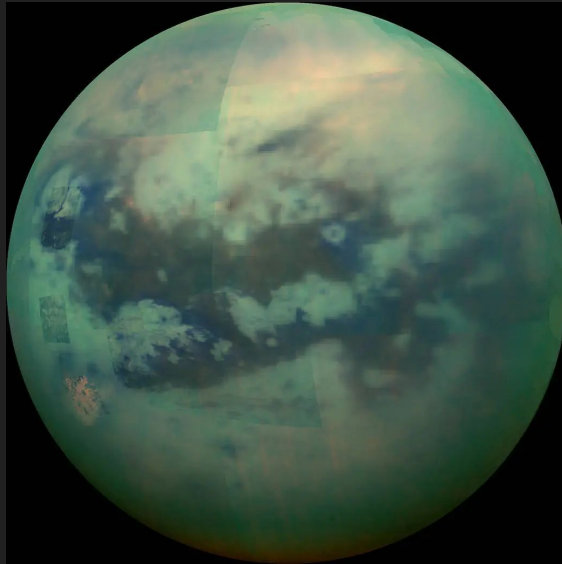


Figure 17: Titan

Jupiter = 2.54 g²¹

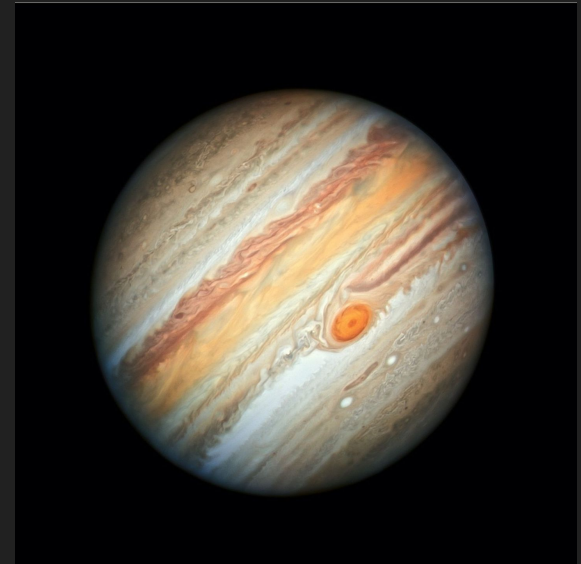


Figure 18: Jupiter

The Square Cube Law

- As size increases, mass grows faster than support area.²³
- Larger bodies face greater structural stress.²³
- Size is limited by mechanics, not just evolution.²³



Figure 19: The bigger they are the harder they fall. 19

Why does the square cube law matter when thinking about alien life in different gravity environments?

- A) It shows that larger organisms become stronger, faster than they gain mass.
- B) It shows that body mass increases faster than supporting surface area as size increases.
- C) It proves that all aliens must be small.
- D) It means gravity does not affect movement as much as chemistry does.

Gravitational Morphology

High Gravity²³

- Shorter broader bodies
- Thicker limbs
- Lower center of mass



Figure 20: Rocky from Project Hail Mary

Low Gravity²³

- Taller or longer limbed bodies
- Lighter build
- Reduced need for weight bearing²⁴



Figure 21: Low gravity alien

Skeletal and Muscular Mechanics

- Bones adapt to mechanical loading.²⁵
- Unloading reduces bone mass and strength.²⁶
- Muscles also weaken when gravity/load decreases.²⁴



Figure 22: NASA astronaut works out on a resistive exercise device aboard the space station.

Impact Survivability: Falling, Landing, & Injury Risk

- Gravity changes landing forces and fall risk.²⁷
- Safe landing depends on energy absorption.²⁸
- Survivable movement is part of body design.^{27,28}



Figure 23: Catching yourself falling

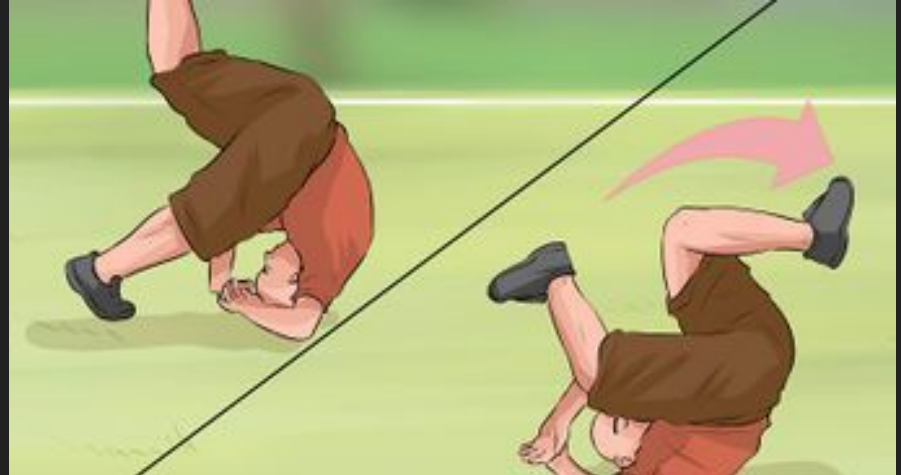


Figure 24: Rolling out of fall

A Biomechanically Plausible Alien

- Gravity shapes morphology.^{23,24}
- The square cube law limits size and structure.^{23,25}
- Survivability filters which bodies actually work.^{24,25,27}



Figure 26: Alien from Paul



Figure 25: Yoda from Star Wars



Figure 27: Aliens from Arrival

A night photograph of several radio towers with satellite dishes and red lights, set against a starry sky and dark trees. The towers are illuminated from below, and the sky is filled with stars. The word "Questions?" is written in white serif font in the lower right quadrant.

Questions?