Life's Mechanism

the self-regulating conversion of thermodynamic disequilibria into directed motion

Simon Pierce

https://orcid.org/0000-0003-1182-987X

UNIVERSITÀ DEGLI STUDI DI MILANO

DOI: 10.3390/life13081750

What is Life?

Living things are characterized by the capacity for:

- Homeostasis (self-regulation)
- Organisation
- Metabolism
- Growth
- Adaptation
- Response to stimuli
- Reproduction
- Agency (acting with purpose)

The growth of silver crystals on the surface of copper from a solution of silver nitrate.
Bilovitskiy CC BY-SA 4.0 Deed

Video : Thomas Bresson CC BY-SA 4.0 Deed

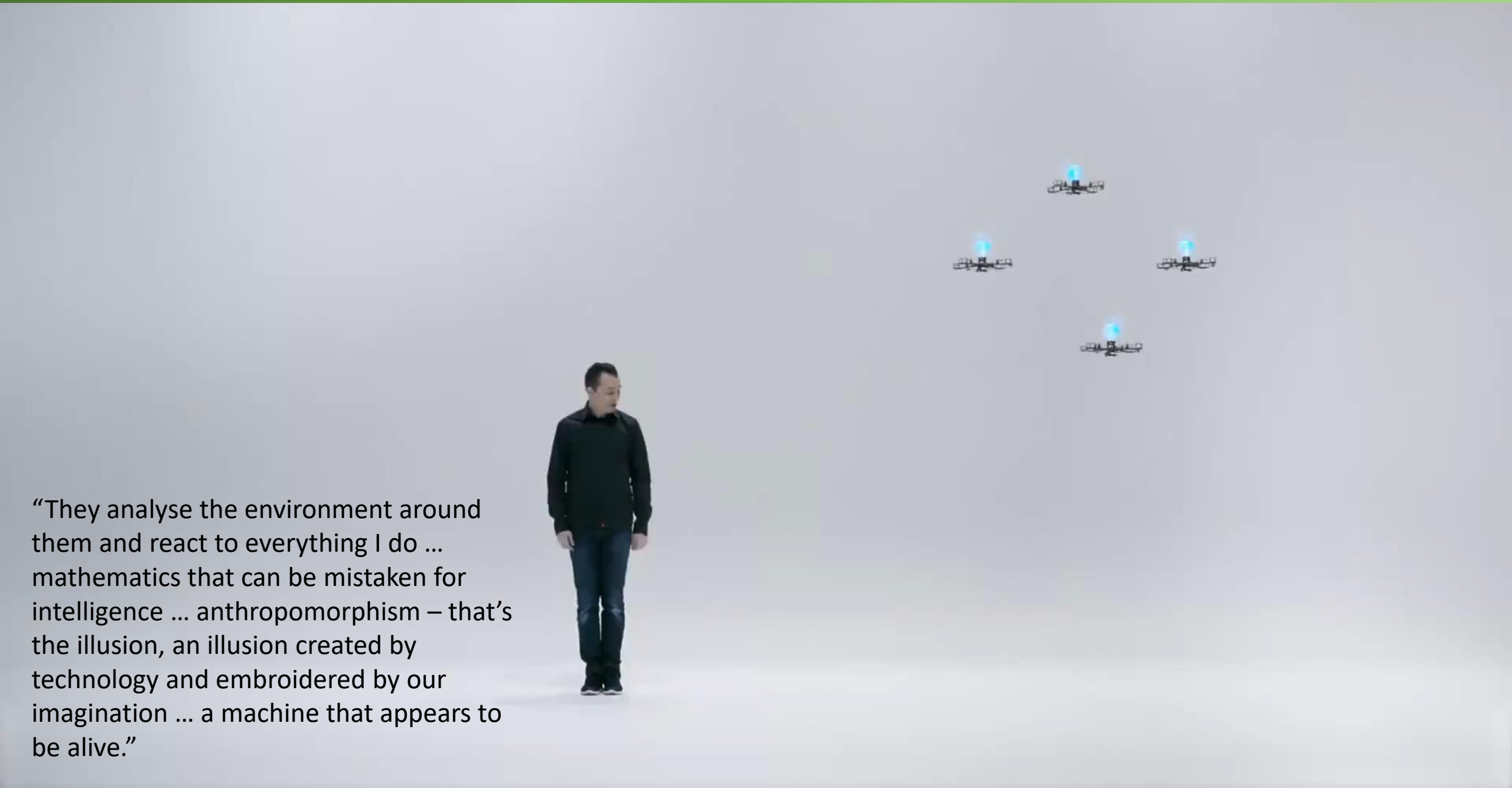
The fallacy of agency (acting with purpose)

Monod, J. Le Hasard et la Nécessité: Essai sur la Philosophie Naturelle de la Biologie Modern; du Seuil, C., Ed.; Points Essais: Paris, France, 1970; p. 248. ISBN 9782020028127.

The fallacy of agency

The fallacy of agency

"A machine that appears to be alive"



"They analyse the environment around them and react to everything I do … mathematics that can be mistaken for intelligence … anthropomorphism – that's the illusion, an illusion created by technology and embroidered by our imagination … a machine that appears to be alive."

The fallacy of agency

Characteristics of life

Living things are characterized by the capacity for:

- Homeostasis (self-regulation)
- Organisation
- Metabolism
- Growth
- Adaptation
- Response to stimuli
- Reproduction
- Agency (acting with purpose)

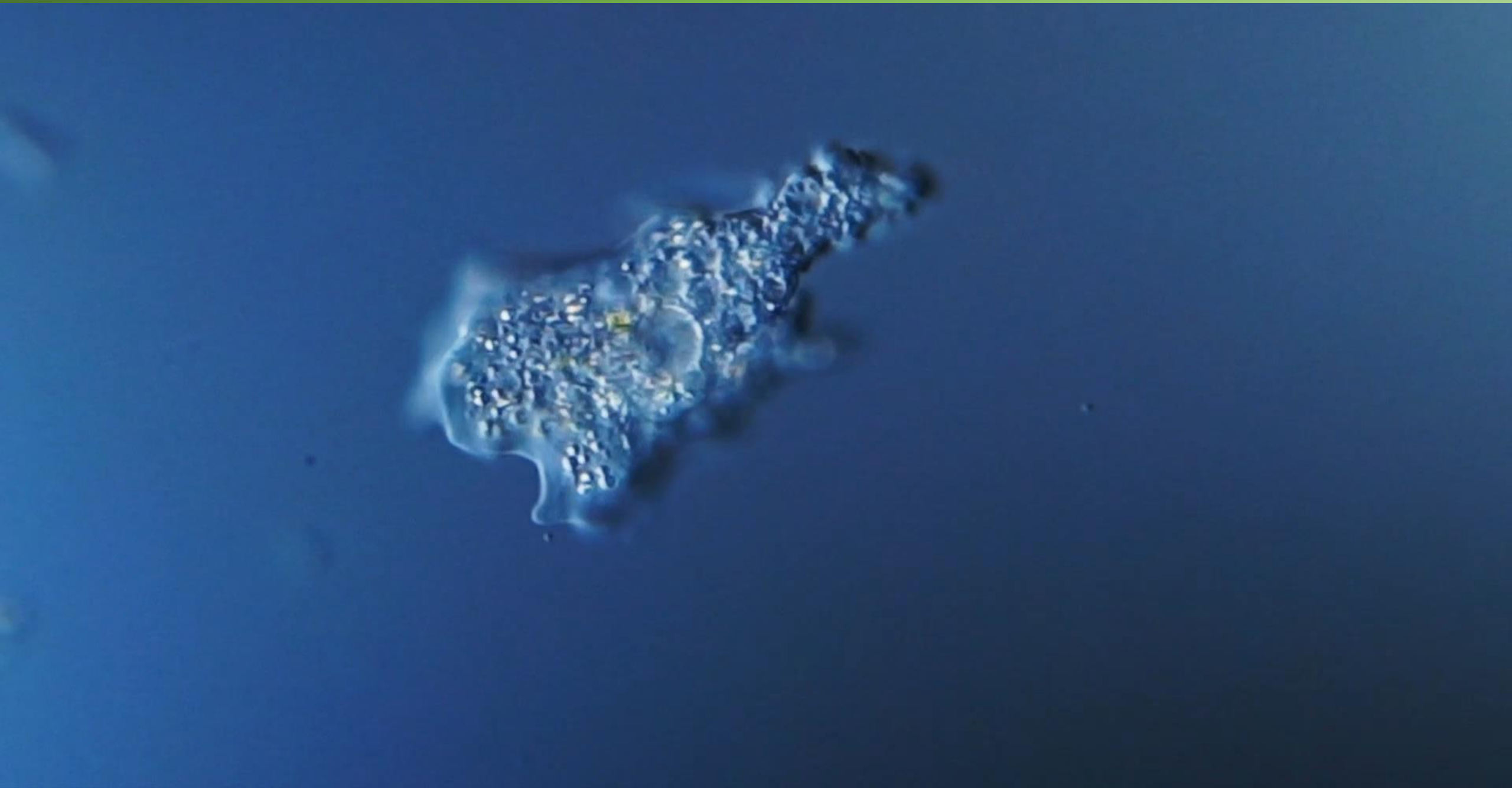
Current theories and definitions of life fail because they focus on secondary phenomena or emergent properties without successfully discerning the underlying mechanism

Confusion about time: Long-Term *vs.* Immediate Life Processes

NASA/ESA/JPL-Caltech
(public domain)

'life is a self-sustaining chemical system capable of Darwinian evolution'
NASA

The immediate state of ‘being alive’

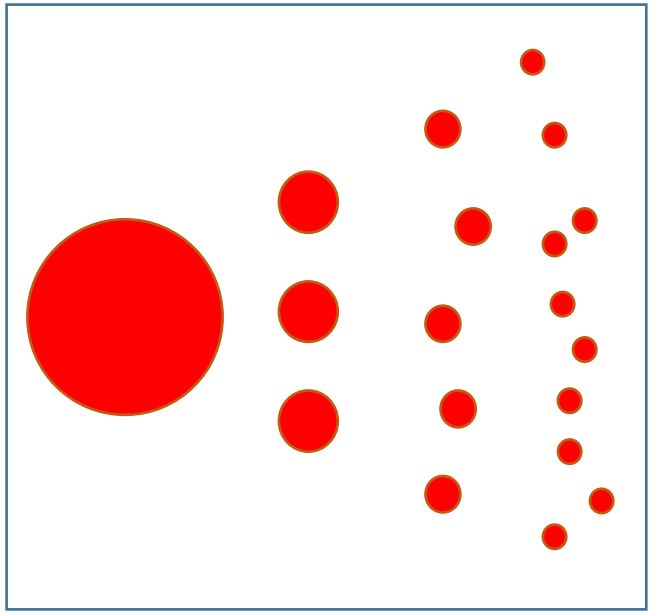


Amoeba under microscope. Differential interference contrast. Ob. 40x
Alexander Klepnev CC BY-SA 4.0 Deed

An essential feature of life: Life reduces entropy

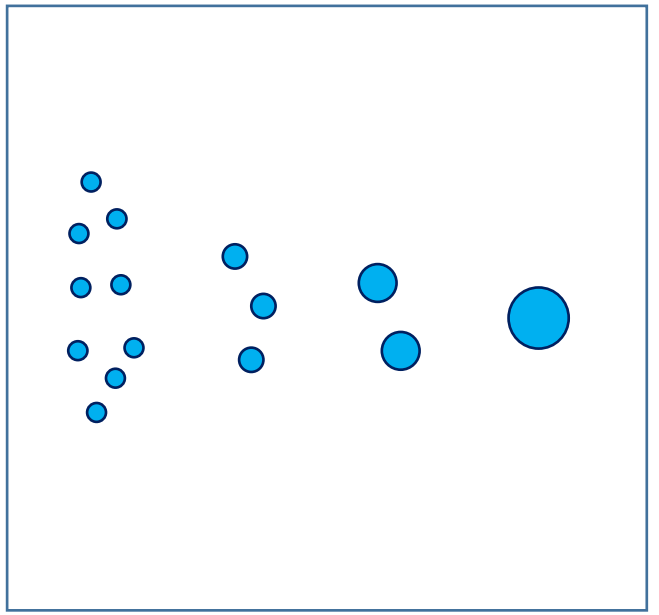
Schrödinger, E. What is Life? Cambridge University Press: Cambridge, UK, 1944; p. 194.

The universe
(entropy or disorder increase with time)



Time →

Living systems
(locally, entropy decreases with time, at least temporarily)



Time →

Life is a process that orders matter in a universe in which matter and energy tend to dissipate

Biological organisms use external energy and matter to accumulate organized structures (cells, tissues, bodies); locally ordered matter that literally embodies reduced entropy [“*negative entropy*”].

Life is a kinetically stable dynamic reaction network

Key characteristics of life:

- life maintains stability autonomously by dynamic kinetic means, rather than chemical inertness;
- replication and metabolism appear to have arisen together in networks of molecules (RNA or functionally similar) catalyzing reactions for one another;
- molecules are variable and thus subject to natural selection, with a gradient of increasing complexity and functional effectiveness through time linking simple chemistry to the systems chemistry of living entities

Life is: 'a self-sustaining kinetically stable dynamic reaction network derived from the replication reaction'

Pross, A. What is Life? How Chemistry Becomes Biology; Oxford University Press: Oxford, UK, 2016; p. 224. ISBN 978-0198784791.

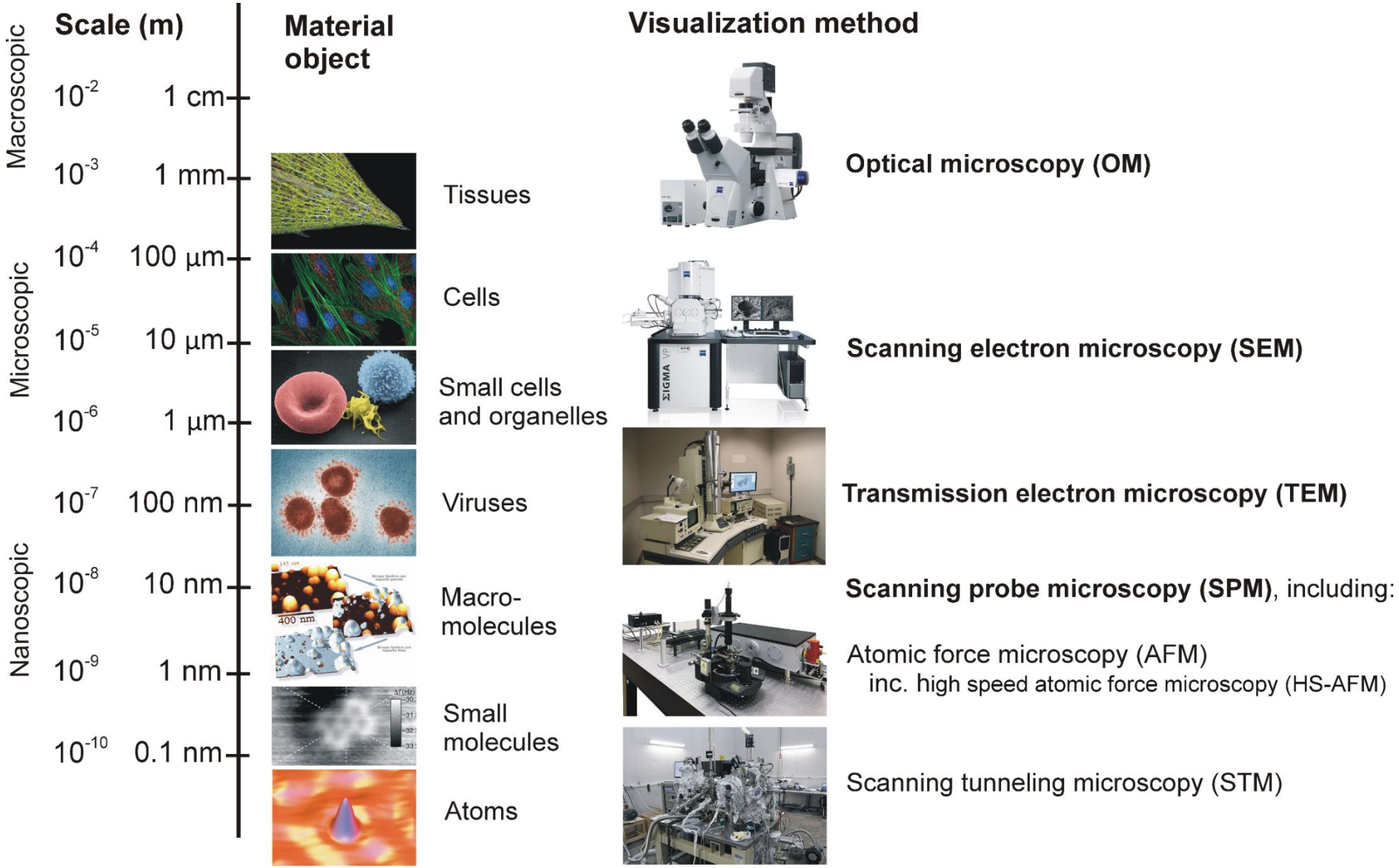
Life is a kinetically stable dynamic reaction network

Life is: 'a self-sustaining kinetically stable dynamic reaction network derived from the replication reaction'

- Life is 'derived from the replication reaction'
- Life is 'kinetically stable'
- Life is a 'dynamic **reaction network**'

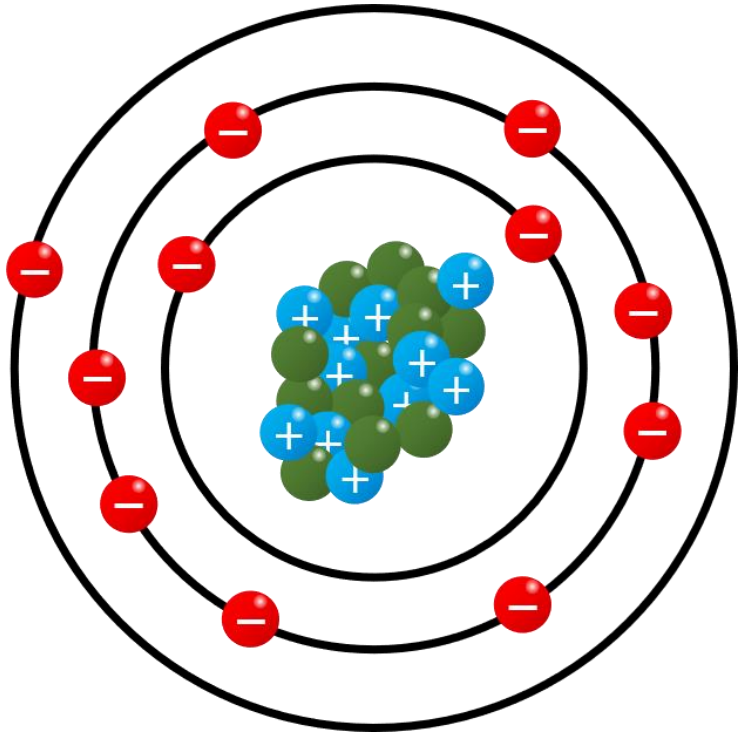
- we know that the real-time operation of reaction networks within cells is governed by a vast array of molecules with different configurations, chemistries, roles and modes of action
- BUT: 'a state of being alive' assumes a single, common principle governing these disparate biological molecules (this is our hypothesis)
- disparate biological molecules have contrasting chemistries, but share common physics (i.e. the state and changes in state of atoms).

Living things are made of atoms and molecules (which we can investigate)



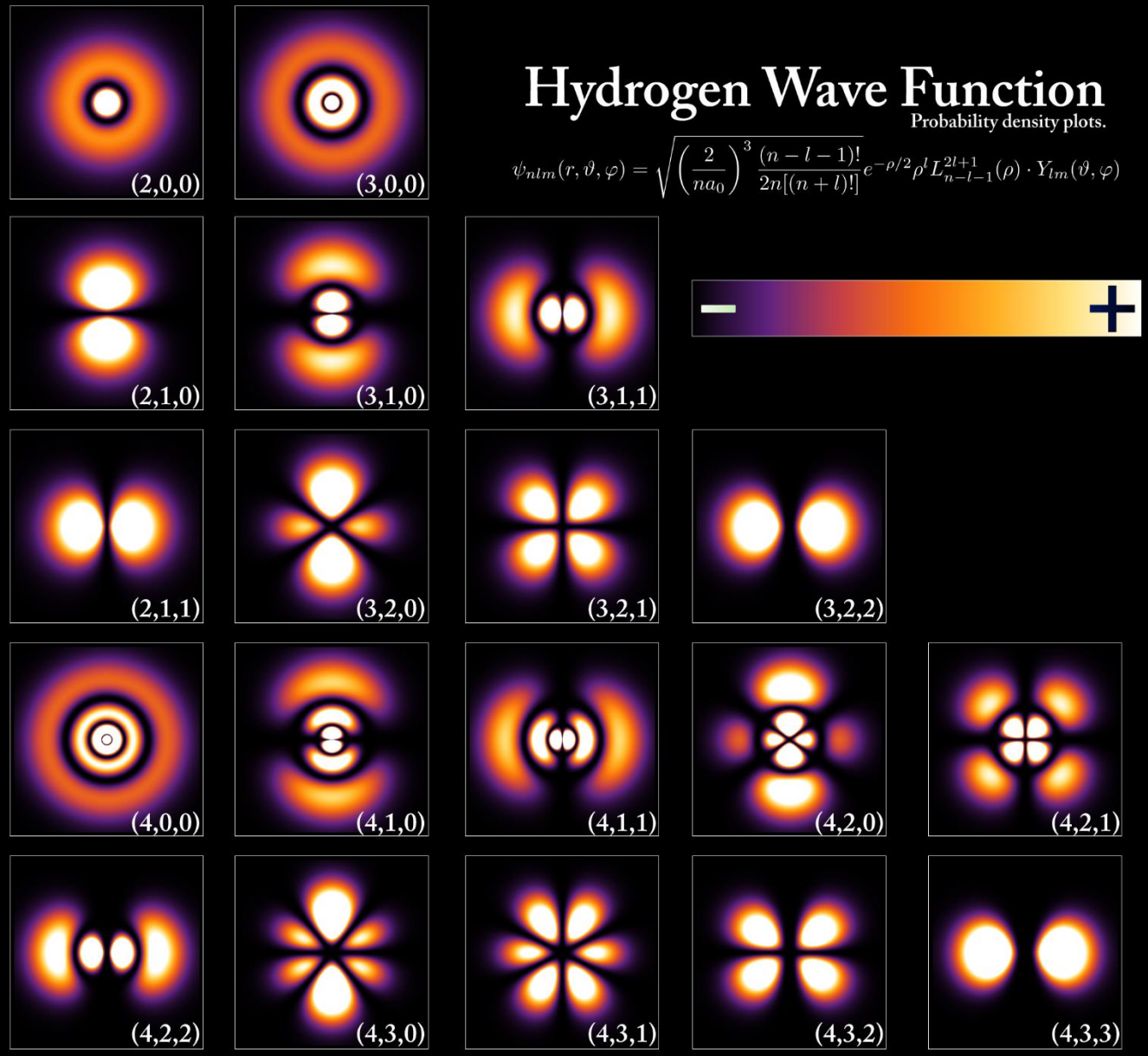
Simon Pierce (2023) Life's Mechanism. ***Life,*** **13(8): 1750.** https://doi.org/10.3390/life13081750

Matter and atoms

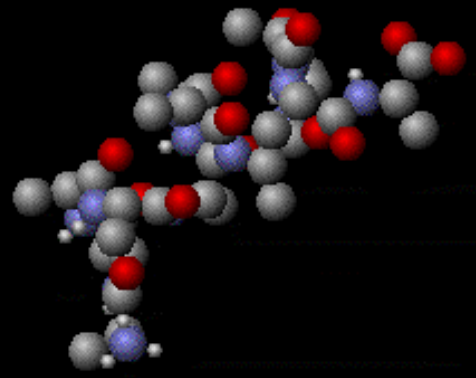


Matter and atoms

Wavefunctions of the electron in a hydrogen atom at different energy levels. Quantum mechanics cannot predict the exact location of a particle in space, only the probability of finding it at different locations. The brighter areas represent a higher probability of finding the electron. PoorLeno (Public Domain)



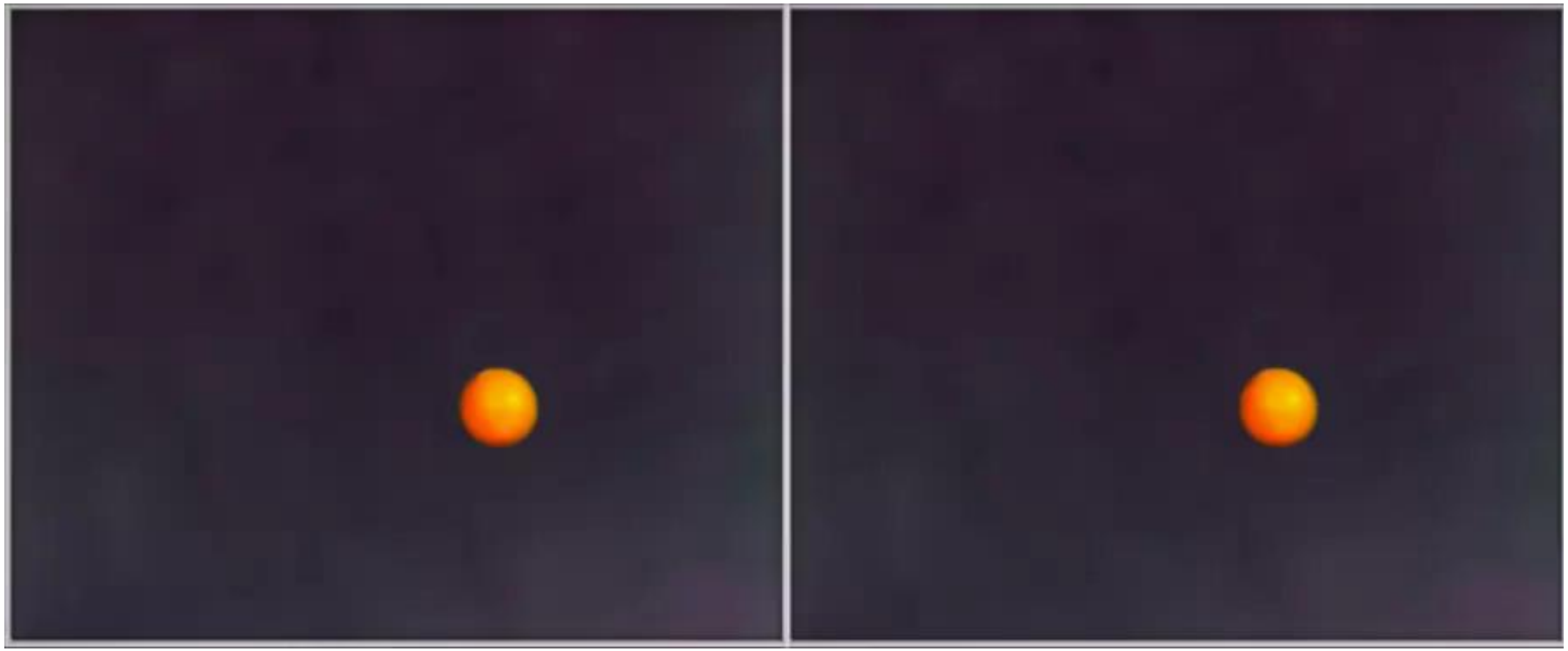
Thermodynamics (thermal motion) is universal



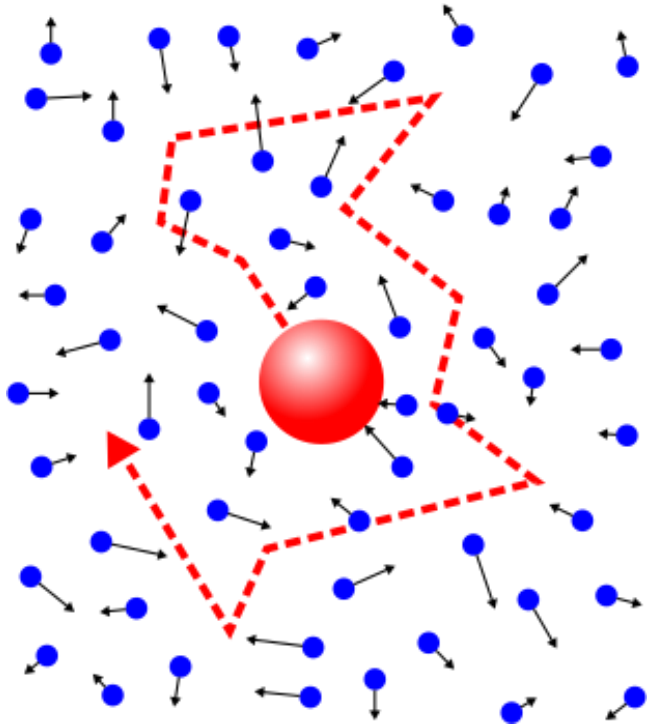
Richard Feynman “Jiggling Atoms”, BBC Archive, broadcast 8 July 1983
www.bbc.co.uk/archive/fun-to-imagine--1-jiggling-atoms/zfkvmfr

Thermodynamics (thermal motion) is universal

Thermal bombardment



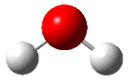
The apparent random motion of atoms, ions or molecules explained. Substances appear to move randomly due to collisions with other substances.
CogentEducator CC BY 3.0 Deed



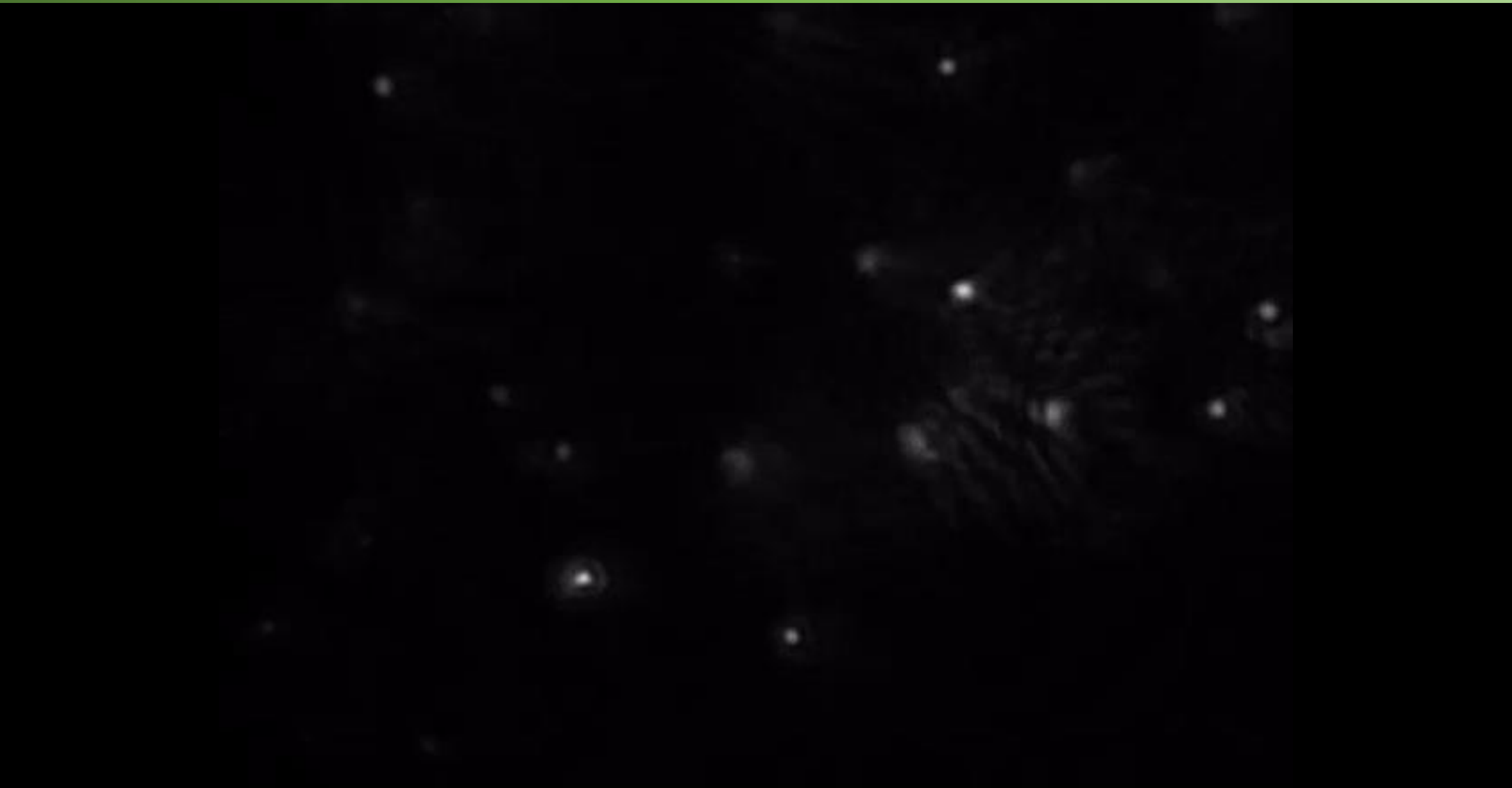
A microscopic particle (red) moves with Brownian motion. It results from collisions with molecules (blue) due to their thermal movement.
2023 Andi schmitt CC BY-SA 4.0 Deed

H_2O vibrational modes: symmetric

asymmetric

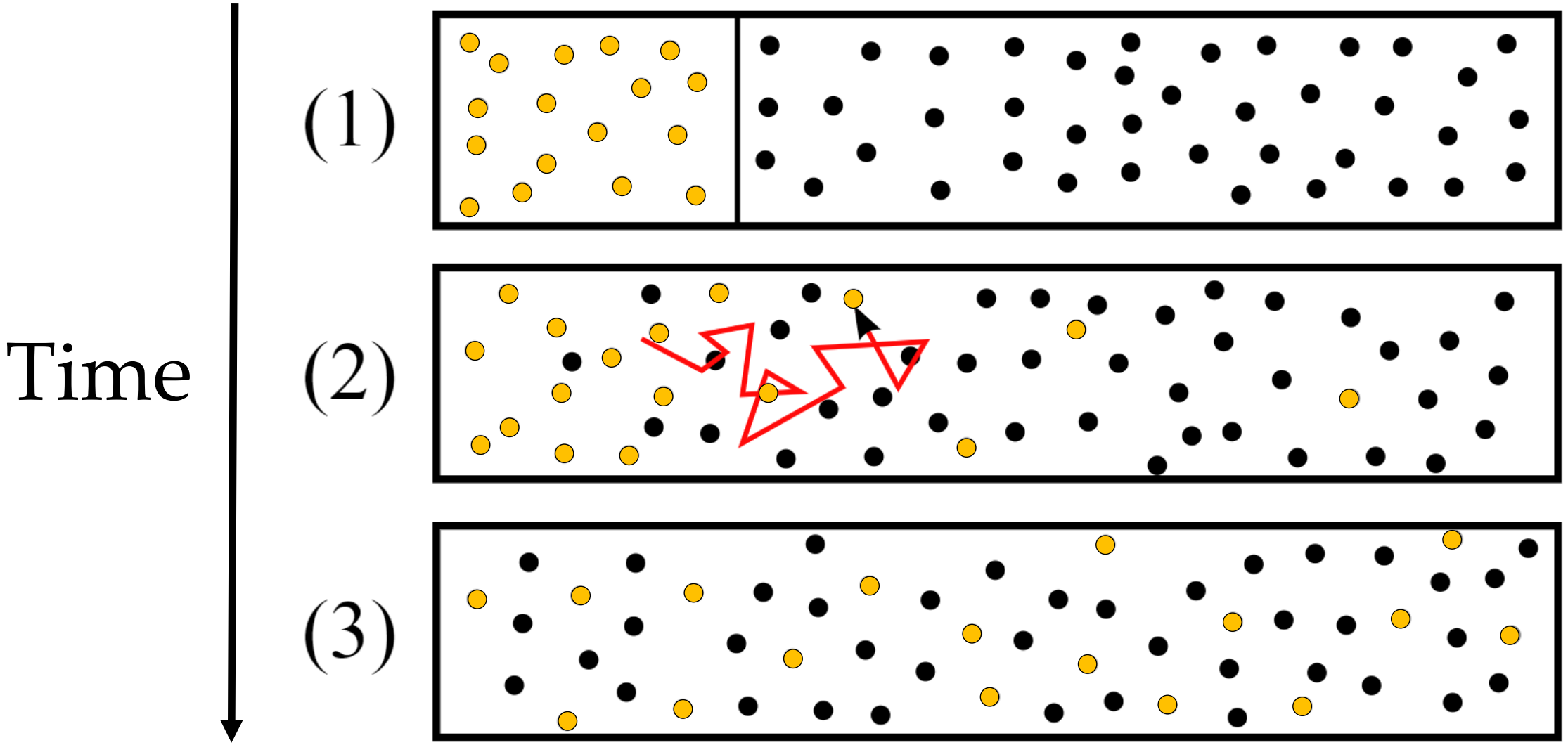


Brownian motion



Brownian motion of 350 nm polymer nanoparticles

Diffusion is described by Brownian motion, driven by thermal motion

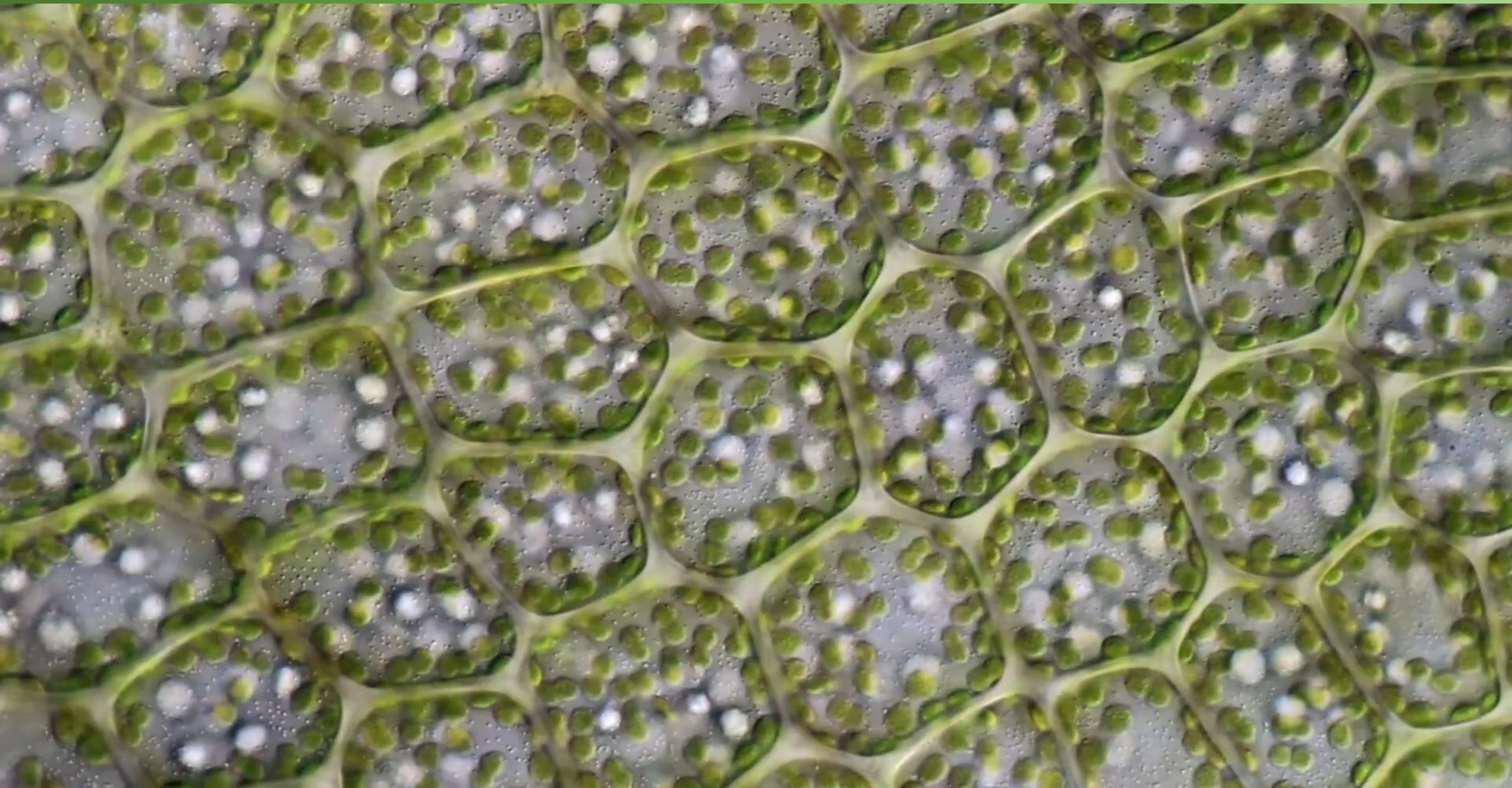


Motion within cells

Amoeba under microscope. Differential interference contrast. Ob. 40x
Alexander Klepnev CC BY-SA 4.0 Deed

Motion within cells

Optical sectioning of leaf cells of the liverwort *Lophozia silvicola*, showing chloroplasts (green) and oil bodies (pellucid). The fine-scale movement of the oil bodies is the result of Brownian motion. Video is edited (truncated) to avoid blank segment. Des Callaghan



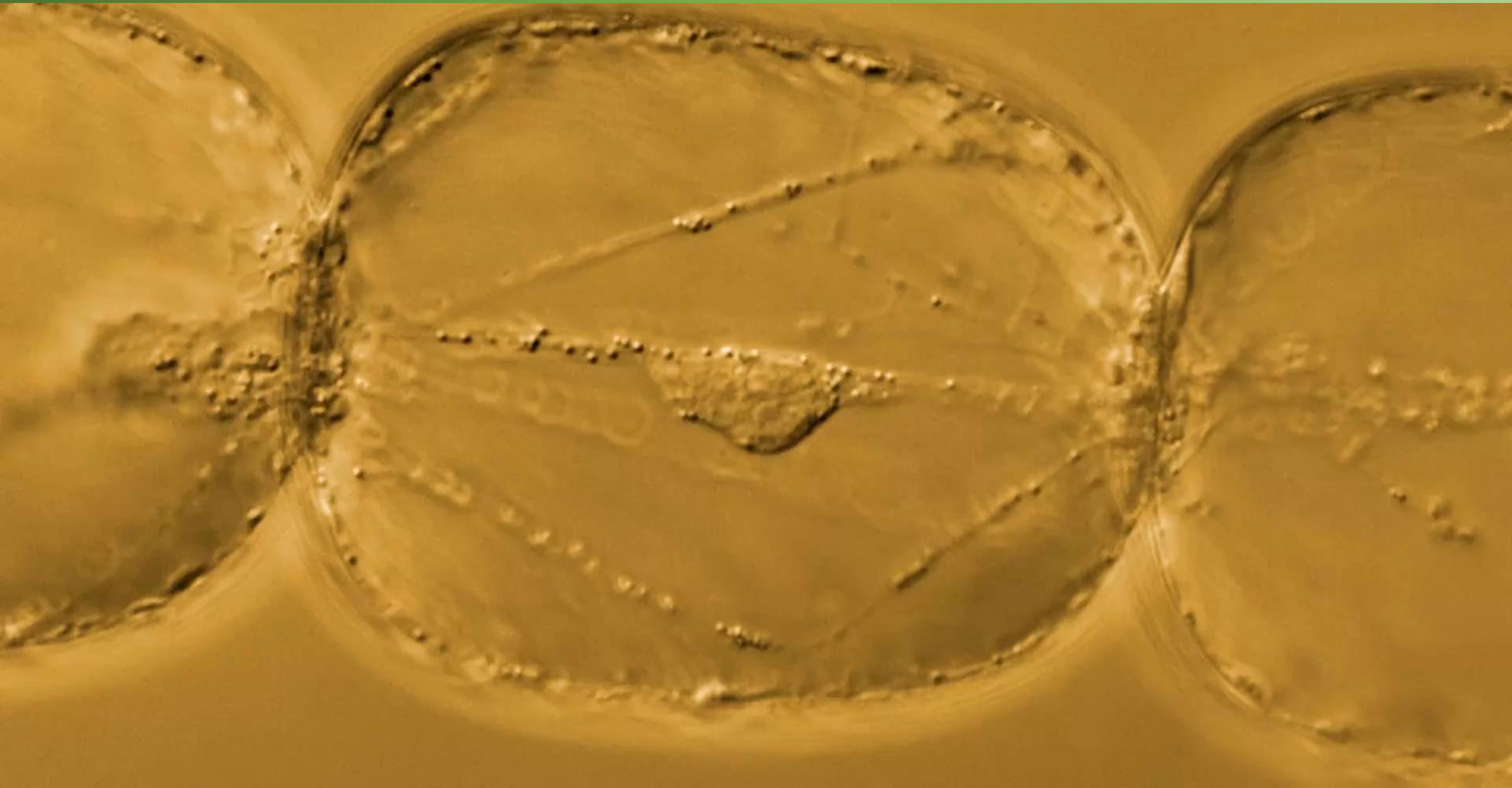
Motion within cells

Cytoplasmic streaming (organized movement of organelles) in onion bulb scale epidermis cells

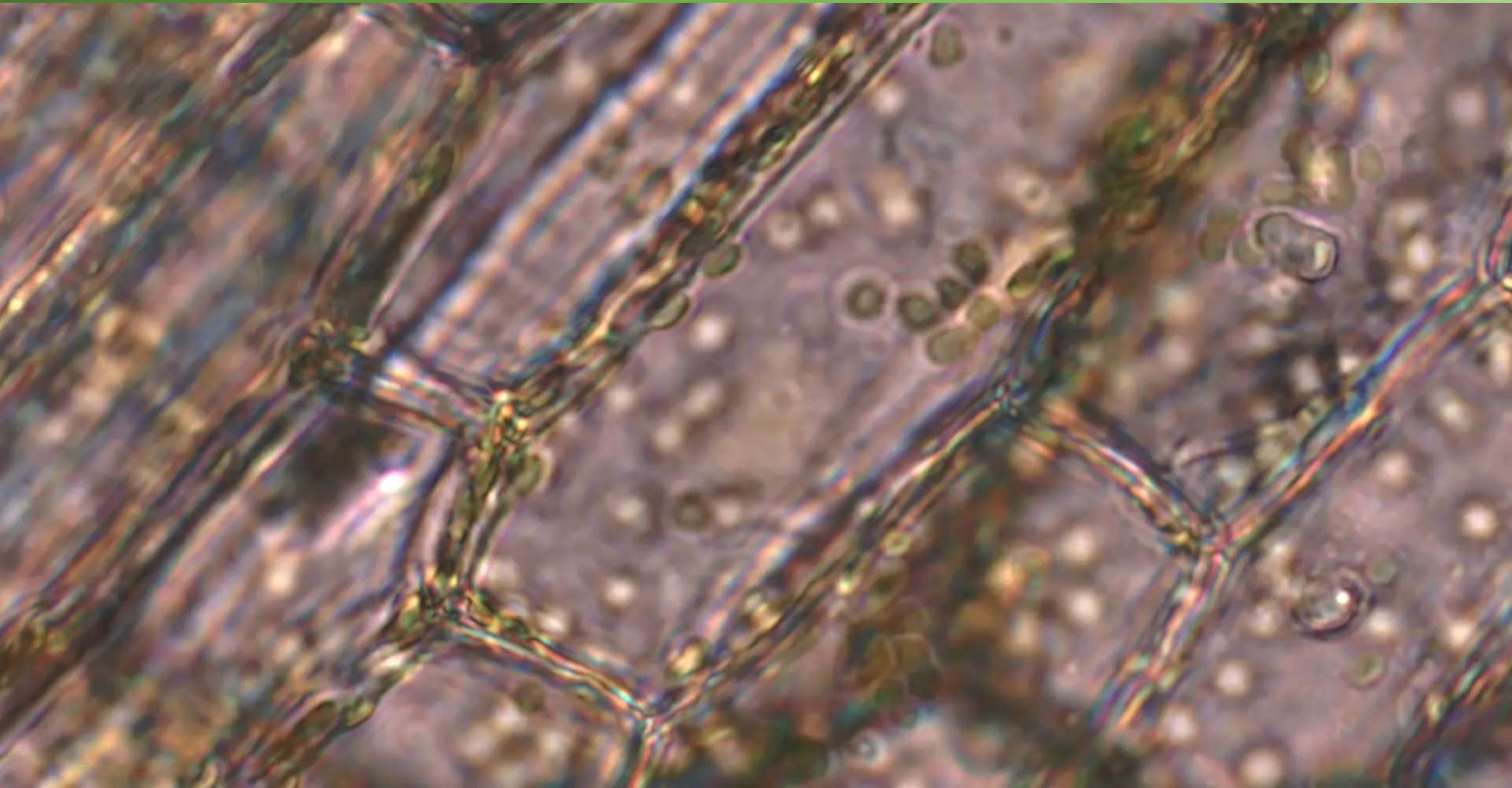
Motion within cells

Cytoplasmic streaming (organized movement of organelles) in onion bulb scale epidermis cells

Motion within cells



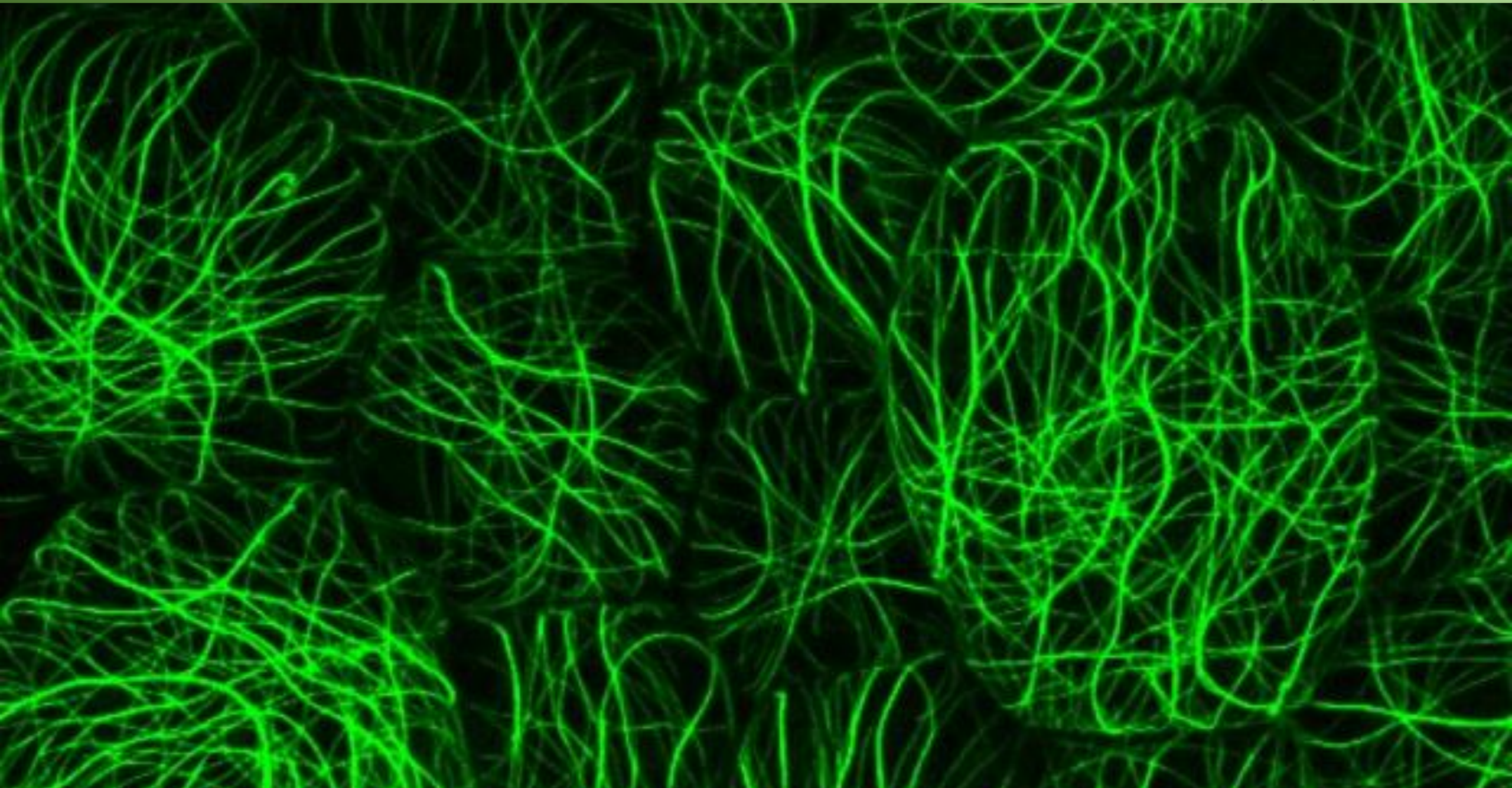
Motion within cells



Cytoplasmic streaming in *Egeria densa*
Berkshire Community College Bioscience Image Library CC0 1.0 Deed Universal

The cytoskeleton

Confocal image of cortical microtubule net in epidermal cells of transgenic *Arabidopsis thaliana* hypocotyls expressing green fluorescent protein fused with the microtubule-binding domain. (GFP-MBD).

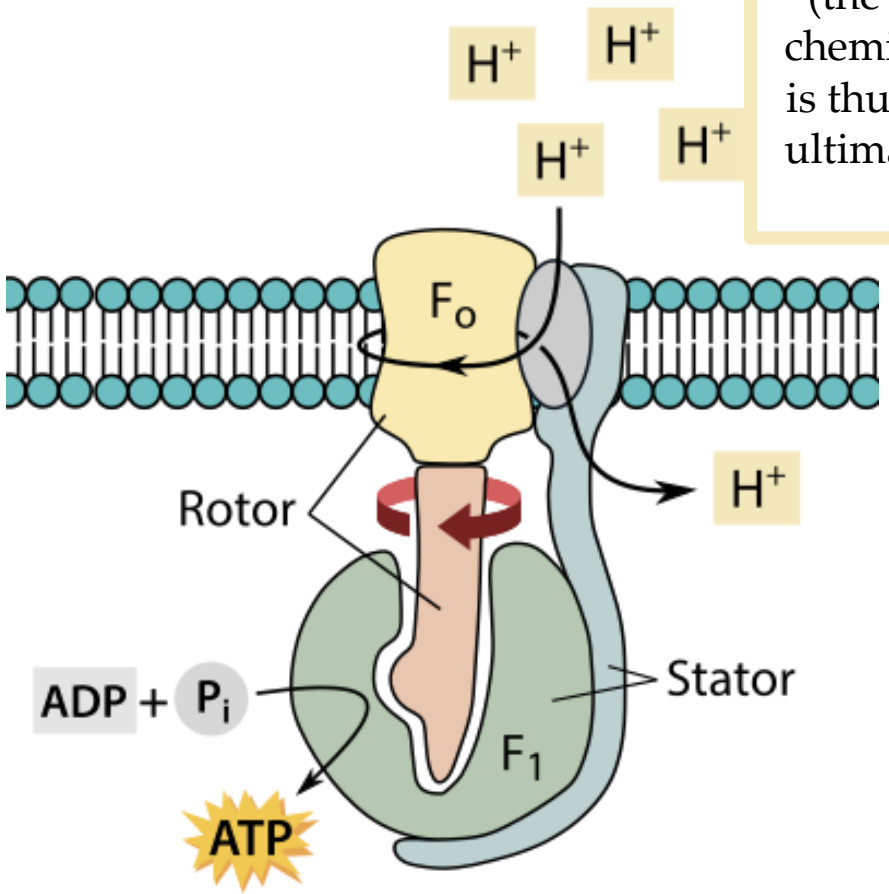


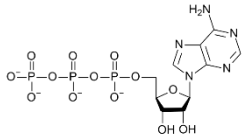
Moving structures within cells

Travel deep inside a leaf
California Academy of Sciences; https://commons.wikimedia.org/wiki/File:Travel_Deep_Inside_a_Leaf_-_Annotated_Version_-_California_Academy_of_Sciences.webm; CC BY 3.0 Deed

Molecular machines: ATP synthase (also ATPases)

Chemiosmosis
(the 'protonmotive force' results from chemical [H⁺] and electric gradients and is thus partially driven by diffusion and ultimately **a thermodynamic difference** or disequilibrium)





adenosine triphosphate (ATP)

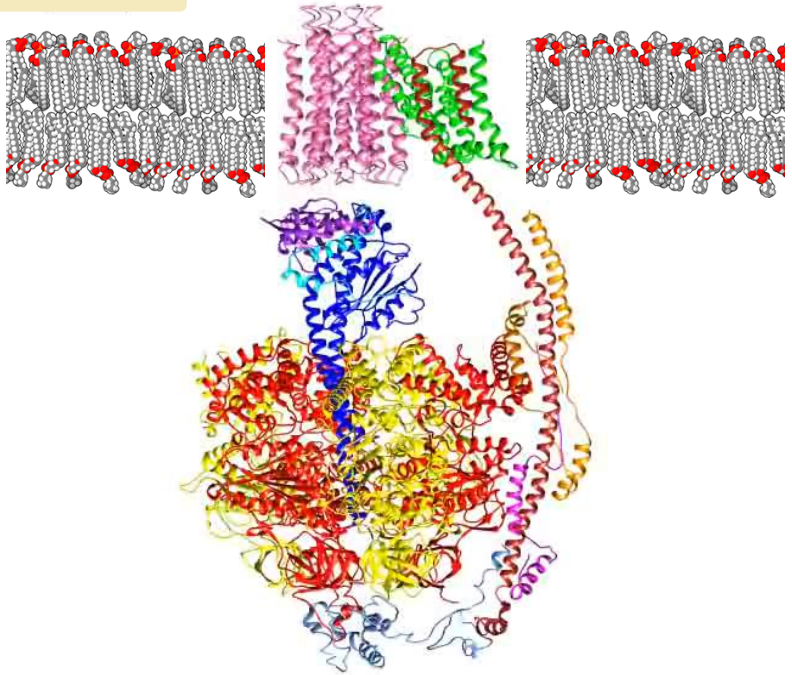
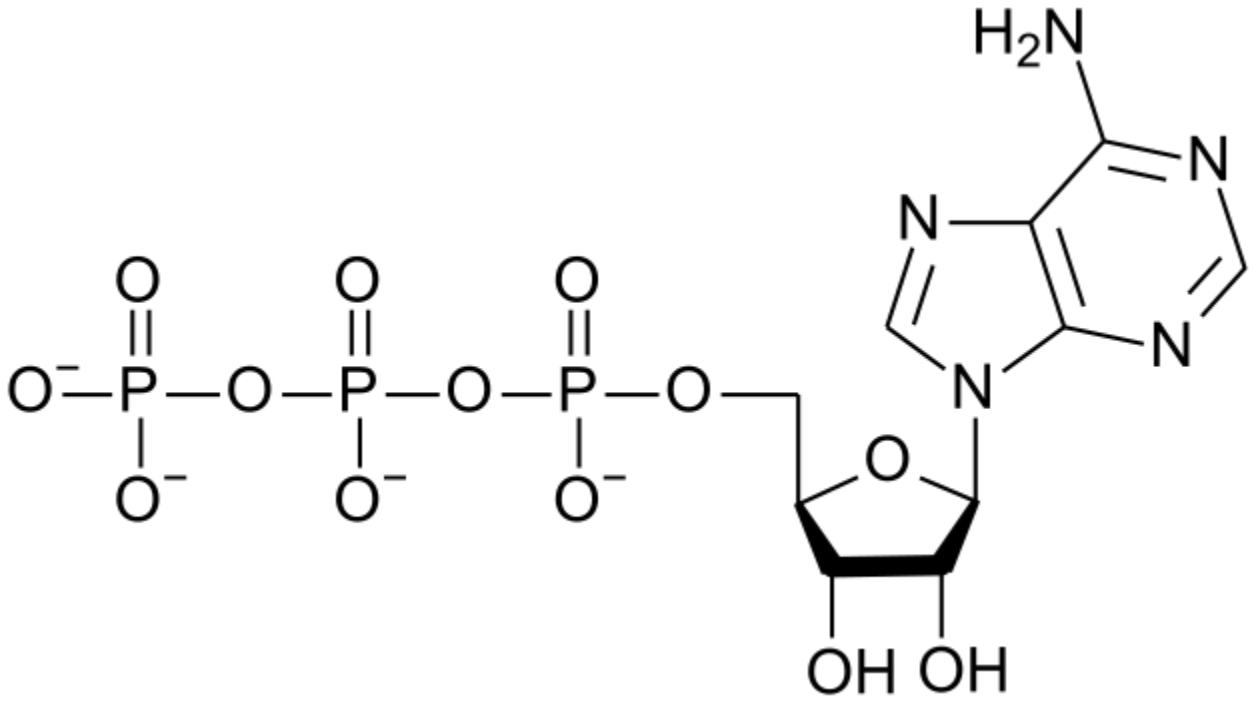


Diagram of the ATP synthase complex. The F0 head is kept stationary while a proton flow across the membrane drives the rotor (orange) that turns inside it. The rotor bears the catalytic sites where ATP is produced from ADP and phosphate.
TheBartgry CC BY-SA 4.0 Deed

Conformation changes of ATP synthase during the rotary cycle.
Anna Zhou, Alexis Rohou, Daniel G. Schep, John V. Bason, Martin G. Montgomery, John E. Walker, Nikolaus Grigorieff, John L. Rubinstein, https://doi.org/10.7554/eLife.10180.013, CC BY-SA 4.0 Deed

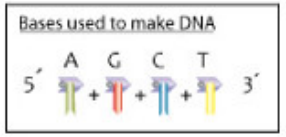
Adenosine triphosphate (ATP)

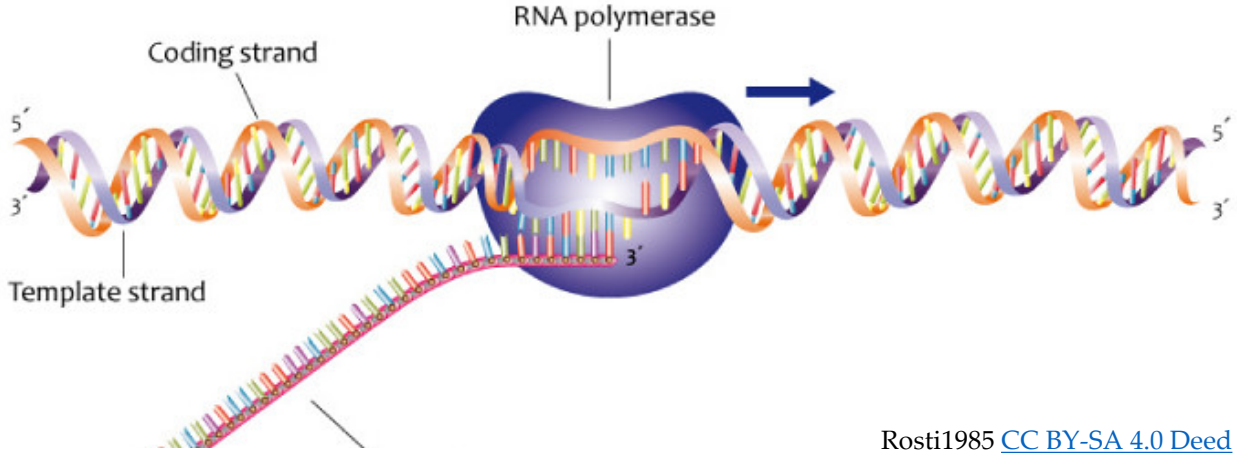


adenosine triphosphate (ATP)

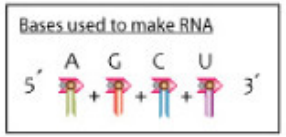
Molecular machines: RNA polymerase during DNA transcription

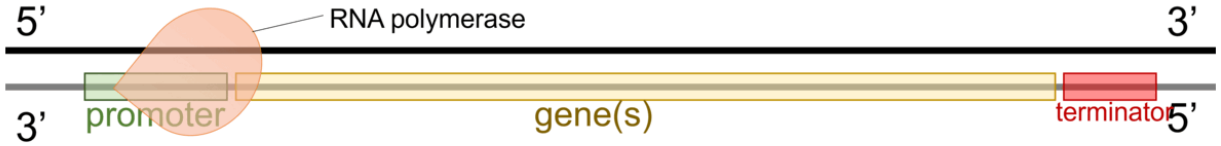
A unidirectional process with ratcheting 'machinery'
Adenosine triphosphate (ATP) drives conformational changes





Rosti1985 CC BY-SA 4.0 Deed



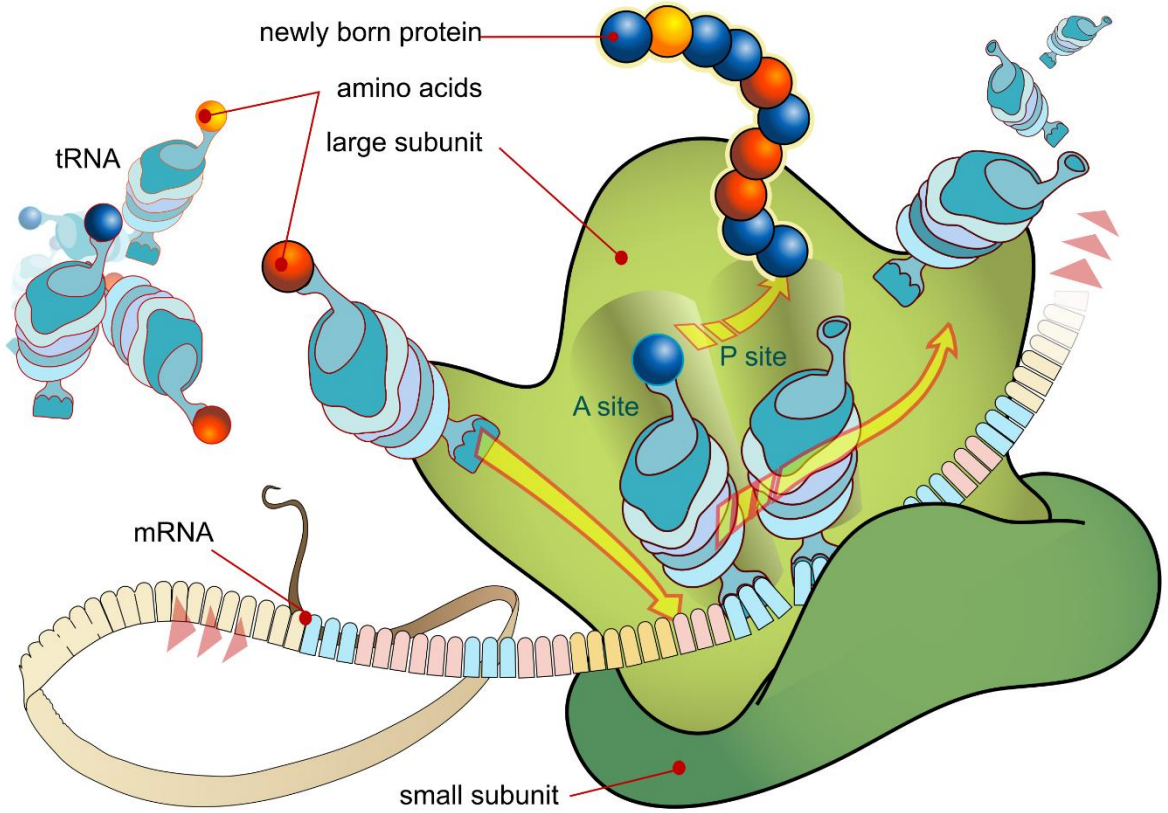


Rosanna Hartline CC BY-SA 4.0 Deed

To see more: Drew Berry (www.drewberry.com)

Molecular machines: Ribosomes during translation (protein synthesis)

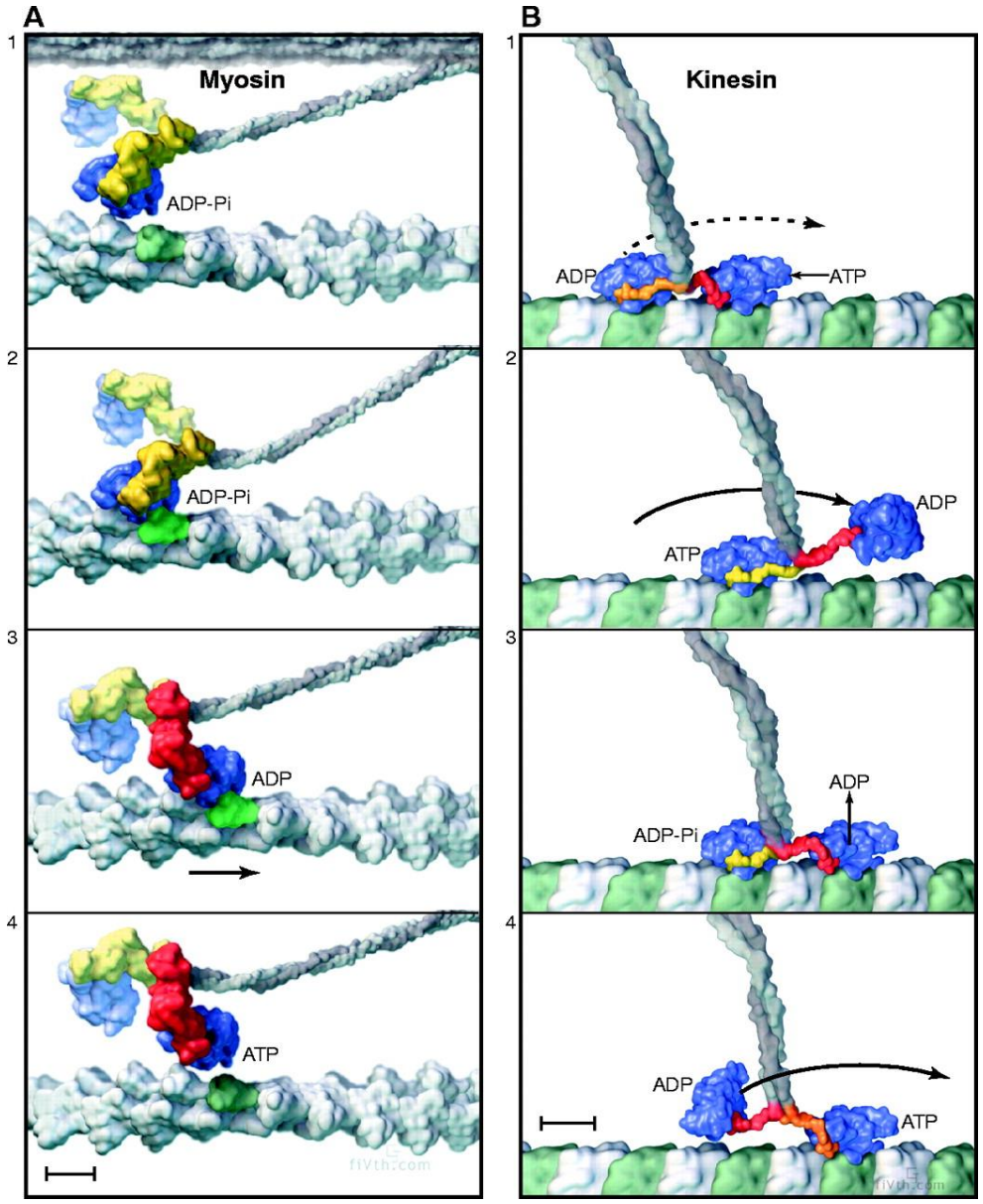
A unidirectional process with ratcheting 'machinery'
Guanosine triphosphate (GTP) drives conformational changes



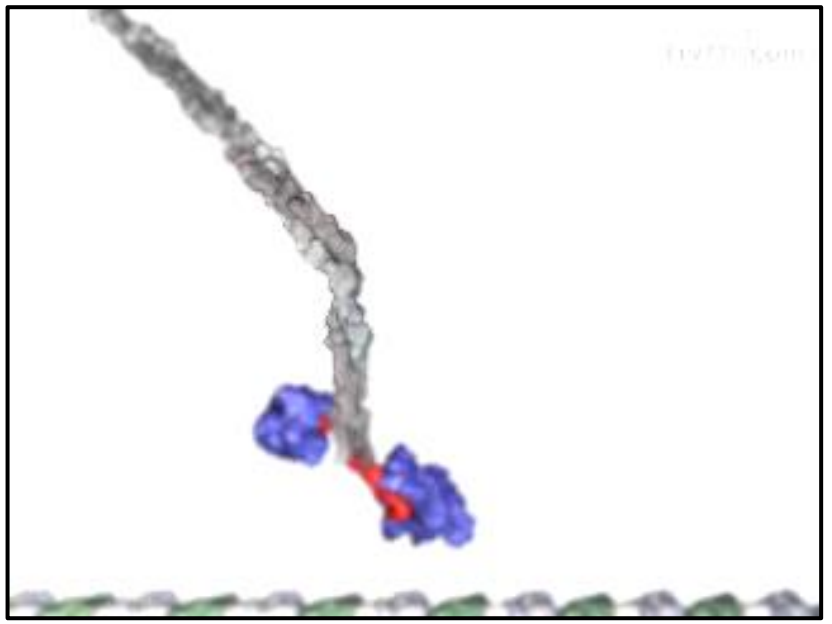
Ratchet-like rotation through 2 degrees of ribosome conformation
Bai X, Fernandez I, McMullan G, Scheres S, https://dx.doi.org/10.7554/eLife.00461.007, CC BY 3.0 Deed

See also: Ratje, A., Loerke, J., Mikolajka, A. *et al.* Head swivel on the ribosome facilitates translocation by means of intra-subunit tRNA hybrid sites. *Nature* **468**, 713–716 (2010). https://doi.org/10.1038/nature09547

Molecular machines of the cytoskeleton: Kinesin



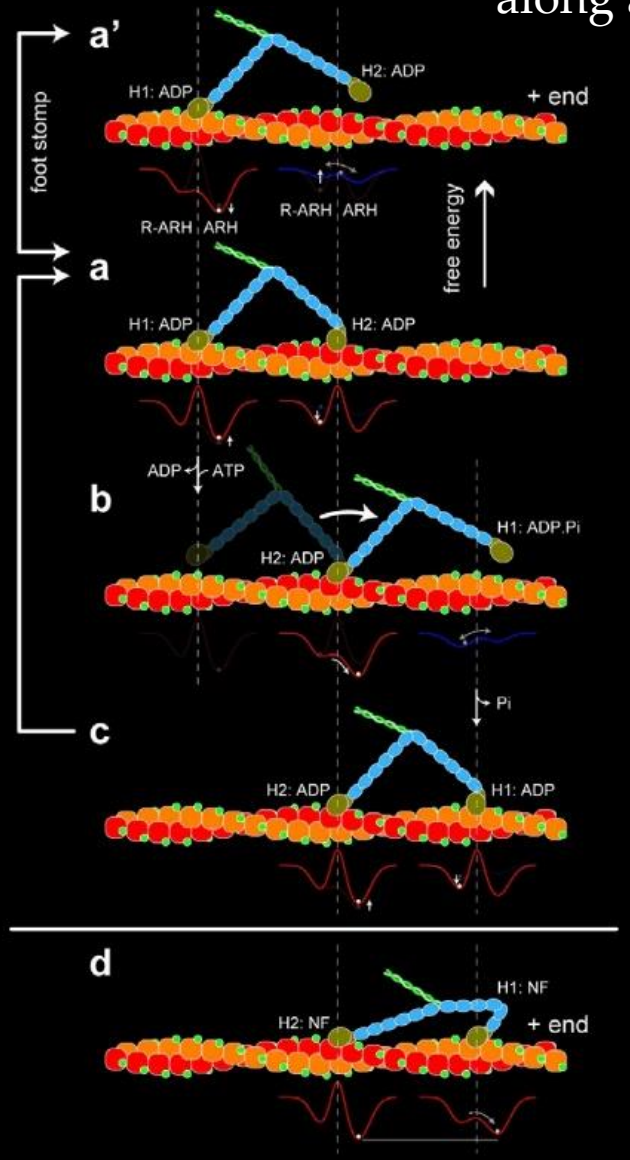
Prof. Ronald Vale (UC San Francisco; UCSF) explains kinesin
www.youtube.com/watch?v=mBo_o0iO68U

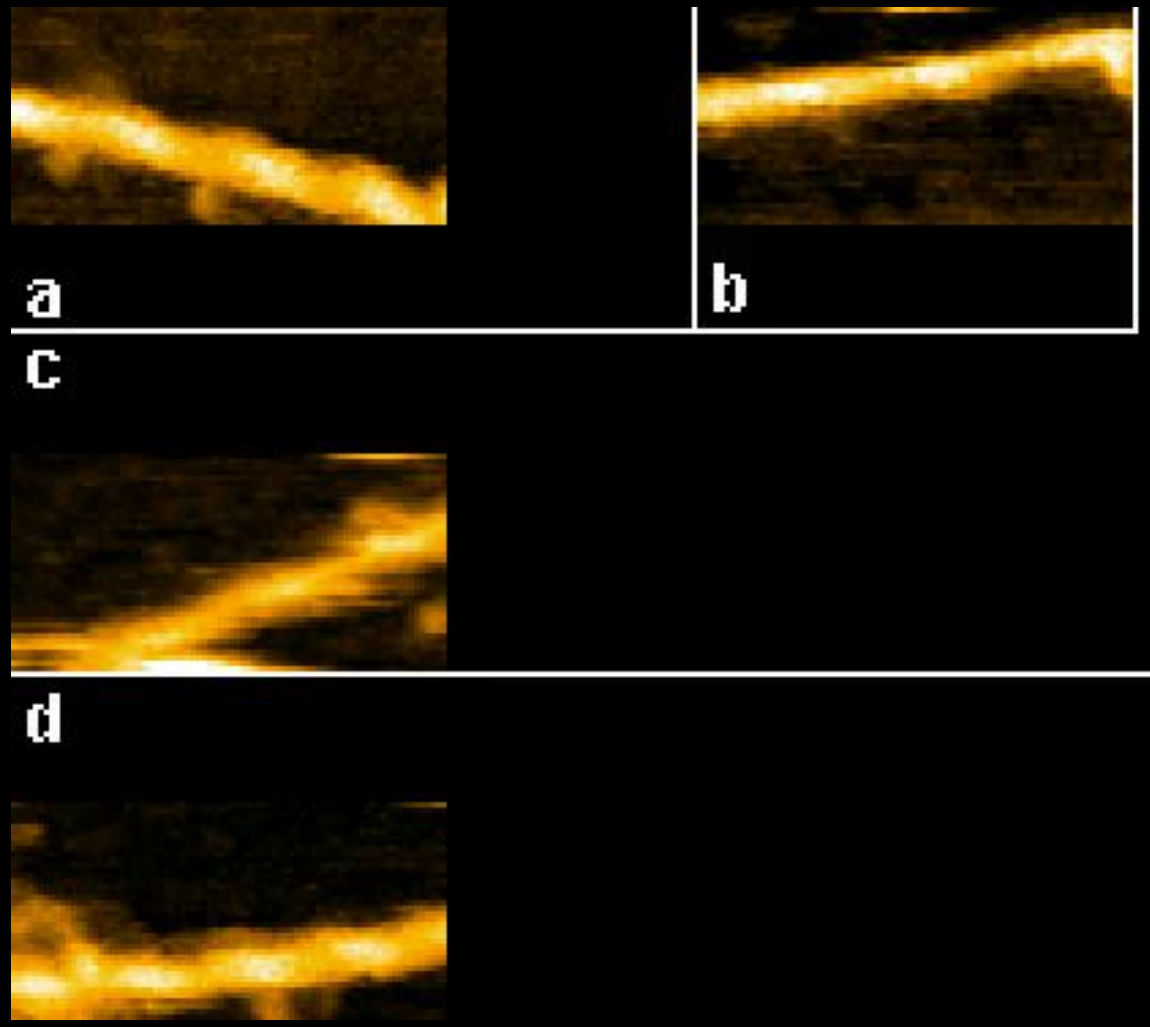


From "Ronald D. Vale, Ronald A. Milligan, The Way Things Move: Looking Under the Hood of Molecular Motor Proteins. Science 288, 88-95(2000). " www.science.org/doi/10.1126/science.288.5463.88

Molecular machines of the cytoskeleton: Myosin

The “rigid hinge” action of **myosin** and “unidirectional processive movement” along an actin filament observed directly with **high speed atomic force microscopy** (HS-AFM)





Kodera, N.; Yamamoto, D.; Ishikawa, R.; Ando, T. Video imaging of walking myosin V by high-speed atomic force microscopy. Nature 2010, 468, 72–77. https://doi.org/10.1038/nature09450

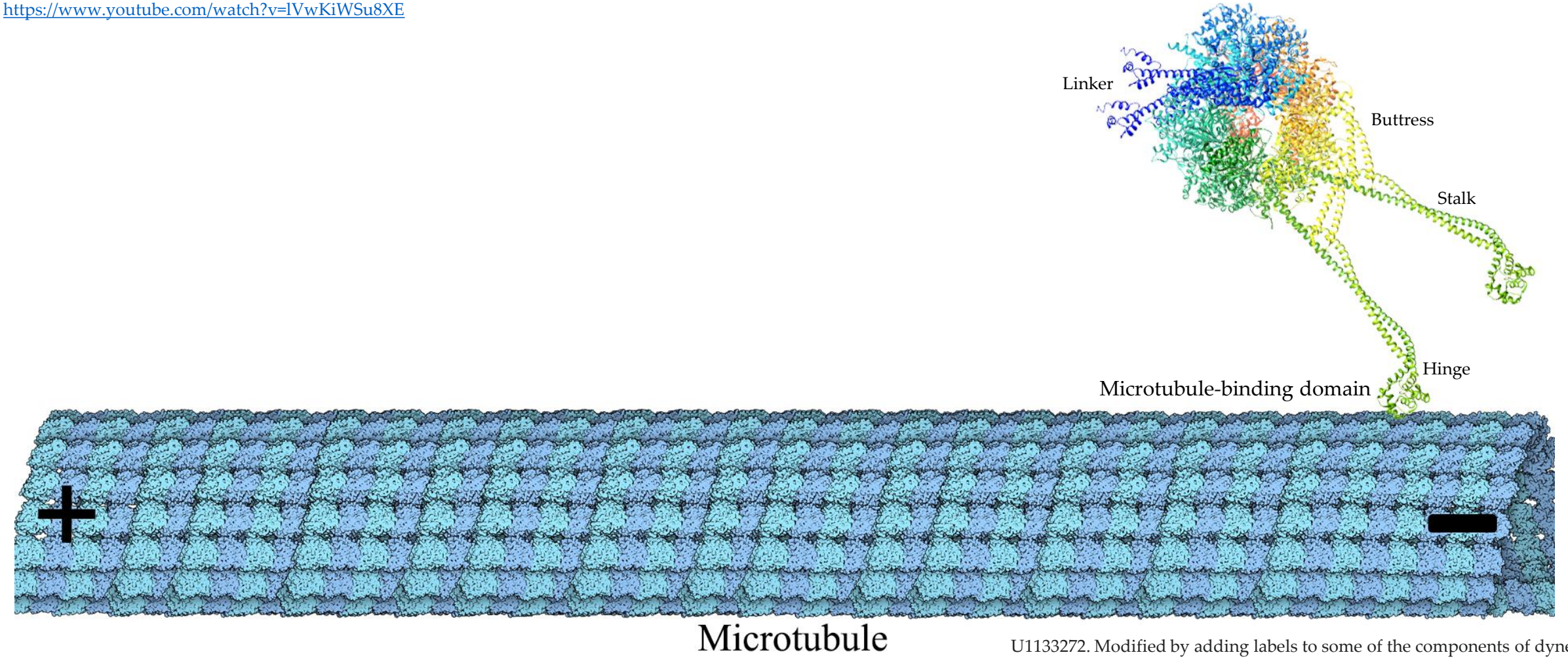
Molecular machines of the cytoskeleton: Dynein

Stan Burgess: a ‘hinge’ motion near the microtubule binding domain

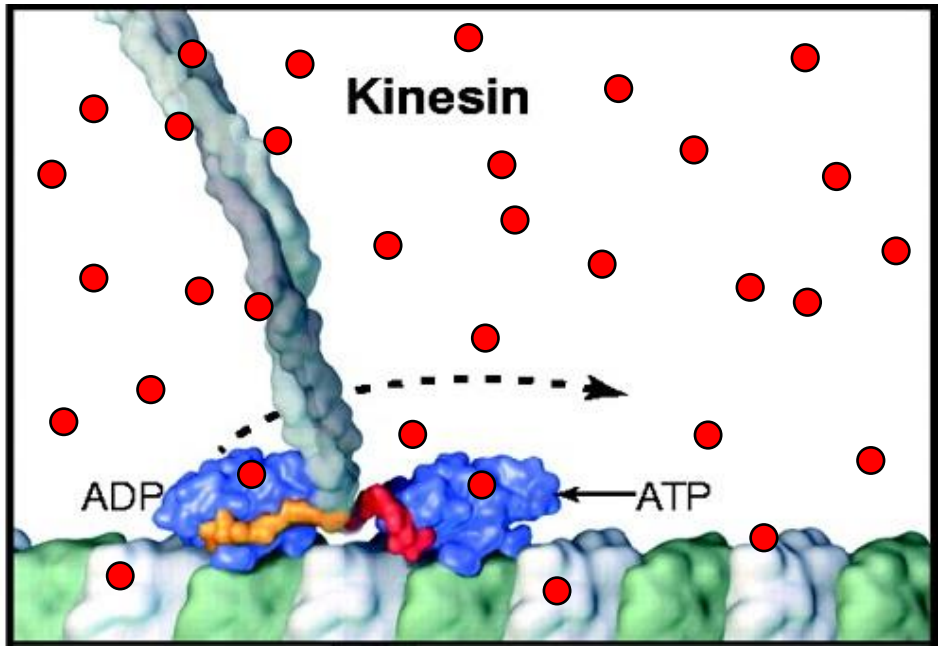
https://www.youtube.com/watch?v=gpjcW-ltOFo&t=70s

Ron Vale: Brownian motion “probably helps this microtubule binding domain to execute a search for new binding sites”

https://www.youtube.com/watch?v=lVwKiWSu8XE

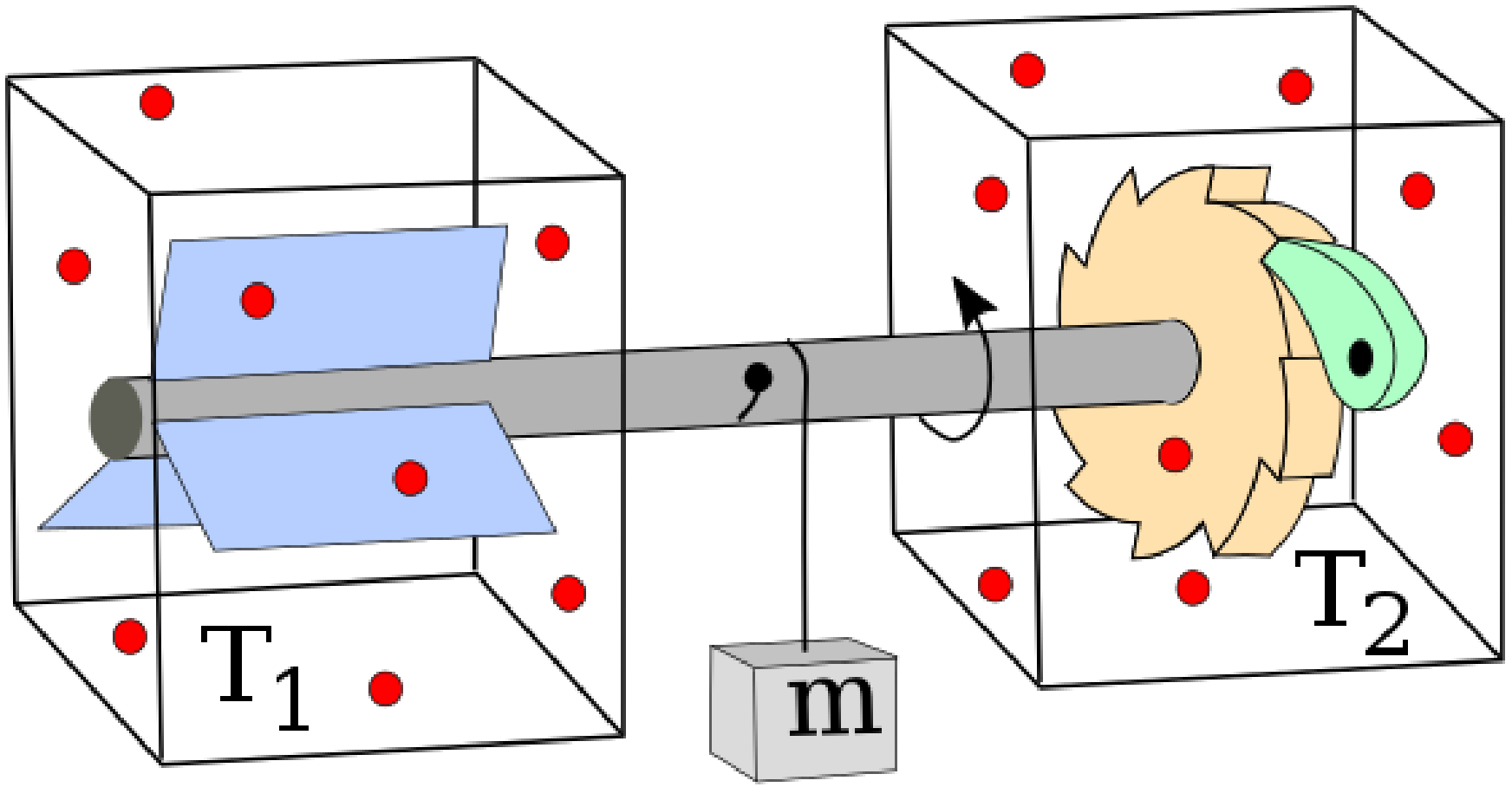


The thermodynamics driving molecular machines



Astumian, R.D. The role of thermal activation in motion and force generation by molecular motors. *Philos. Trans. Royal Soc. B* 2000, 355, 511–522.

Brownian ratchets (heat engines)



Richard Feynman's Messenger Lectures; The Character of Physical Law. Part 5 "The Distinction of Past and Future" (1964); BBC/Cornell University
www.feynmanlectures.caltech.edu/fml.html#5 (video; ratchets explained at 22:30 to 30:00)

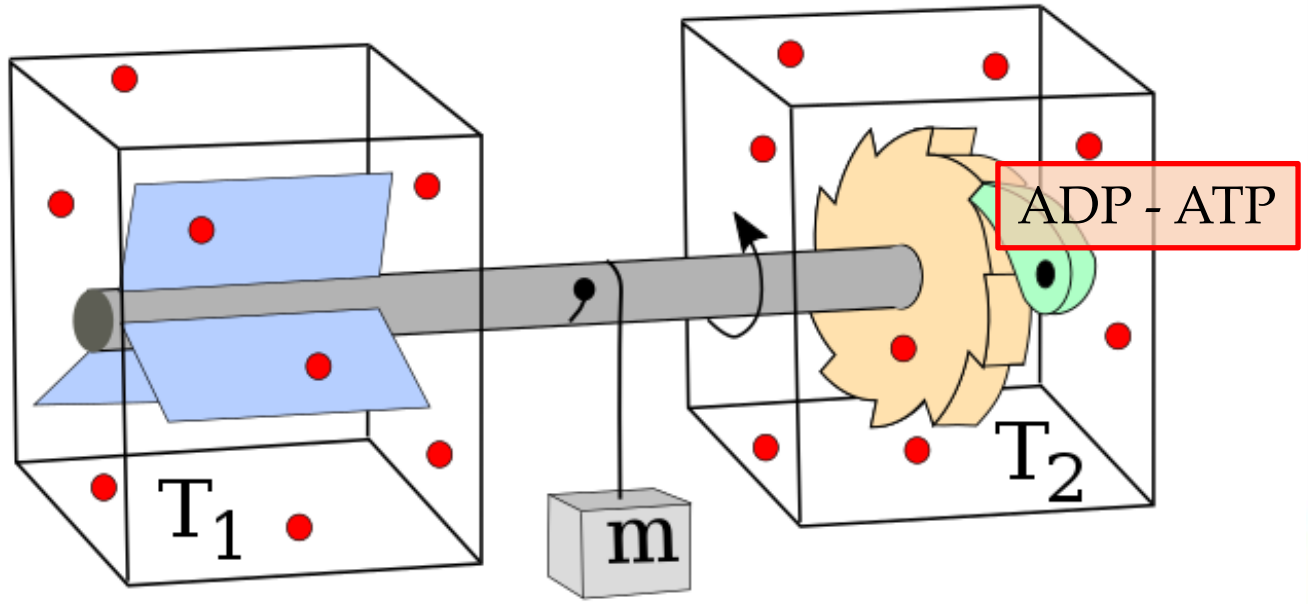
The Feynman Lectures on Physics, Volume I; Lecture #46 "Ratchet and pawl" (5/11/1962); California Institute of Technology
www.feynmanlectures.caltech.edu/I_46.html (text)
www.feynmanlectures.caltech.edu/flptapes.html (audio)

Brownian ratchets

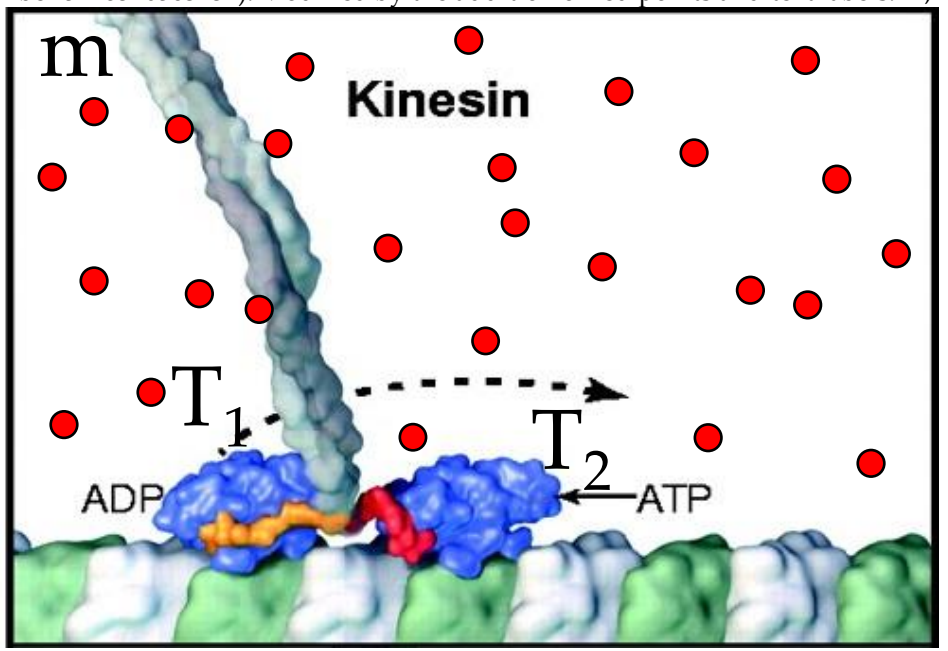
A Brownian Ratchet demo using golf balls, a fan, a paddle wheel, and a clock ratchet. Constructed at Lewis & Clark College by Jamie Wecker (https://www.youtube.com/watch?v=QU2CKQQLDt4).

Conformation helps induce directional motion under agitation

From "Ronald D. Vale, Ronald A. Milligan, The Way Things Move: Looking Under the Hood of Molecular Motor Proteins. Science 288, 88-95(2000). " www.science.org/doi/10.1126/science.288.5463.88
Reprinted with permission from the American Association for the Advancement of Science (AAAS) (License Number 5778310563132). Modified by the addition of red points and text labels: m, T_1 and T_2.



$T_1 > T_2$ = thermodynamic disequilibrium
m = mass (work)

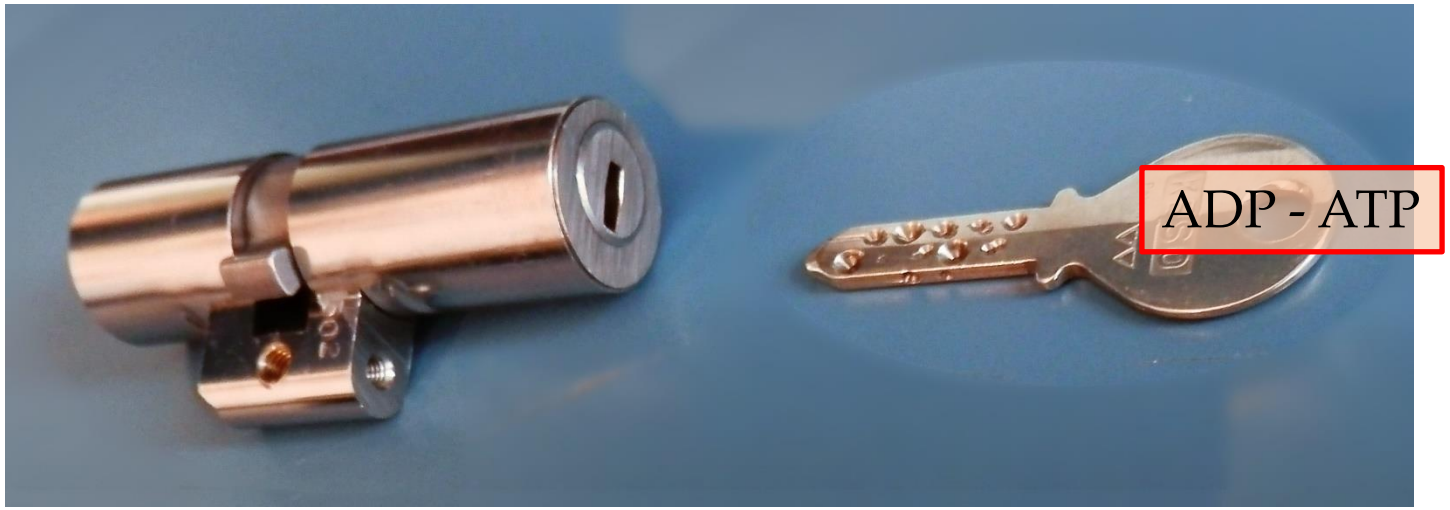


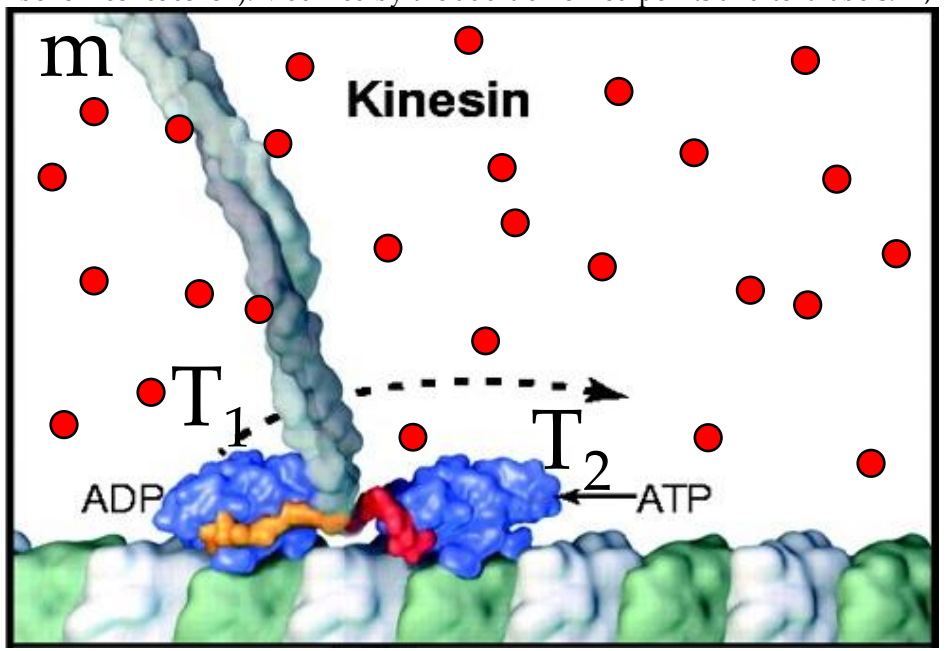
$T_1 > T_2$ = thermodynamic disequilibrium
m = mass (work)

Thermal agitation induces motion, while ATP is a 'missing component' of biological heat engines (the pawl), temporarily completing the configuration, favouring the disequilibrium across the structure and thereby activating it (allows it to be moved by the thermal agitation), with the subsequent motion and work then resetting the configuration. (ADP – ATP represents the two states of the pawl).

Conformation helps induce directional motion under agitation

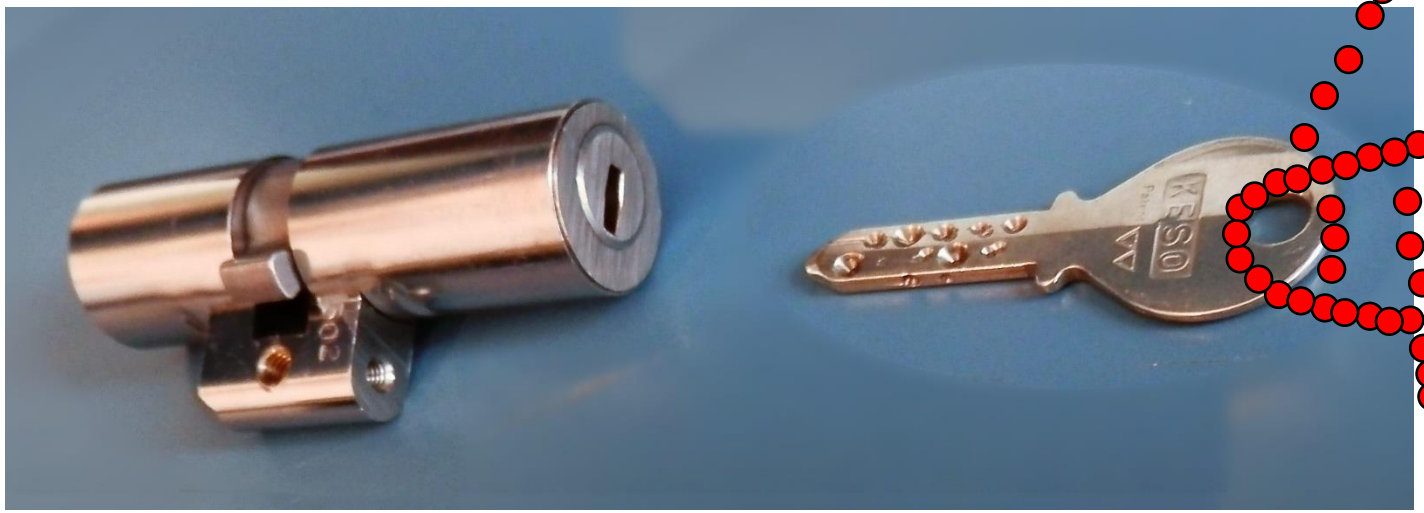
From "Ronald D. Vale, Ronald A. Milligan, The Way Things Move: Looking Under the Hood of Molecular Motor Proteins. Science 288, 88-95(2000). " www.science.org/doi/10.1126/science.288.5463.88
Reprinted with permission from the American Association for the Advancement of Science (AAAS) (License Number 5778310563132). Modified by the addition of red points and text labels: m, T_1 and T_2.

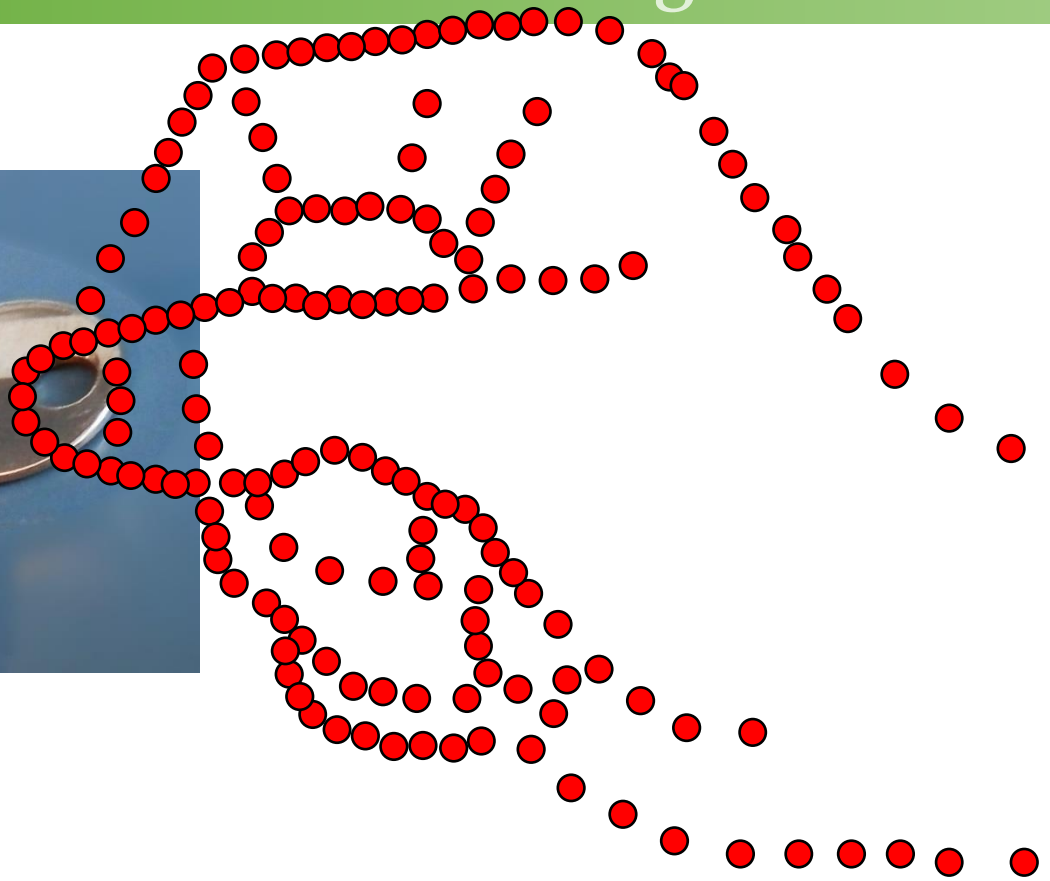




Conformation helps induce directional motion under agitation

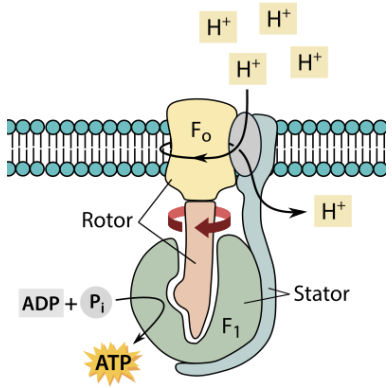
ItalianLocksmith CC BY 3.0 Deed





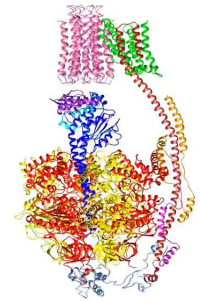
Note that ATP synthase uses diffusion to drive movement

- not all molecular motion is 'powered' by ATP (ATP can't explain all motions in cells);
- the energy source for ATP synthesis is a thermodynamic gradient
- thermal agitation is universal, and is involved in all motions within cells



TheBartgry CC BY-SA 4.0 Deed

Can molecular engines run backwards?



- Rotating enzymes such as ATP synthase or V-ATPase can spin in either direction to create or use ATP (e.g. A-ATPase/synthase of archaea).

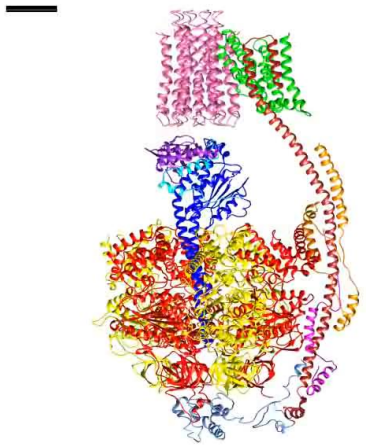
- Molecular motors can take backwards steps (e.g. for **dynein** this is common)

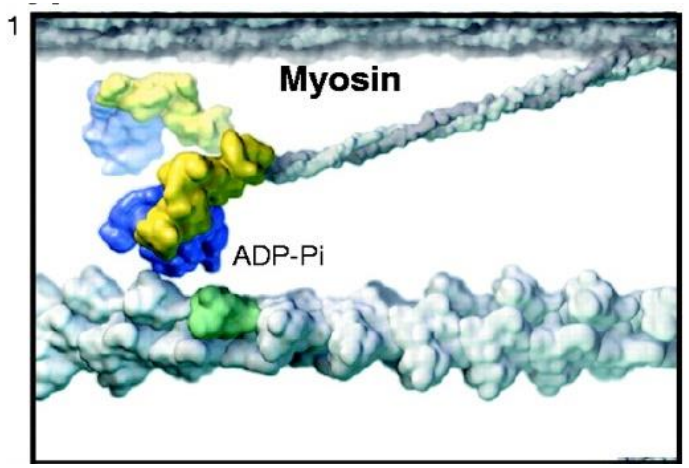
  Reck-Peterson *et al*. (2006) *Cell 126*, 335–348.

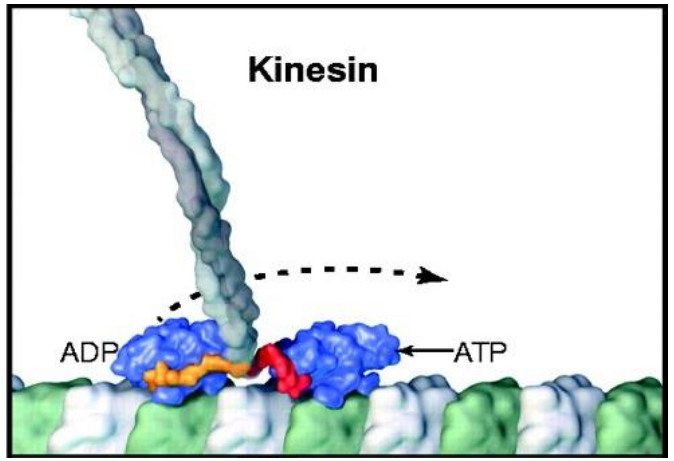
- BUT: possible conformations change continuously due to thermal agitation and are "sampled through motions with a topologically preferred directionality", and tend to proceed in one direction overall.

  Grant *et al*. (2010) *Curr. Opin. Struct. Biol. 20*, 142–147.

Random to directional motion →



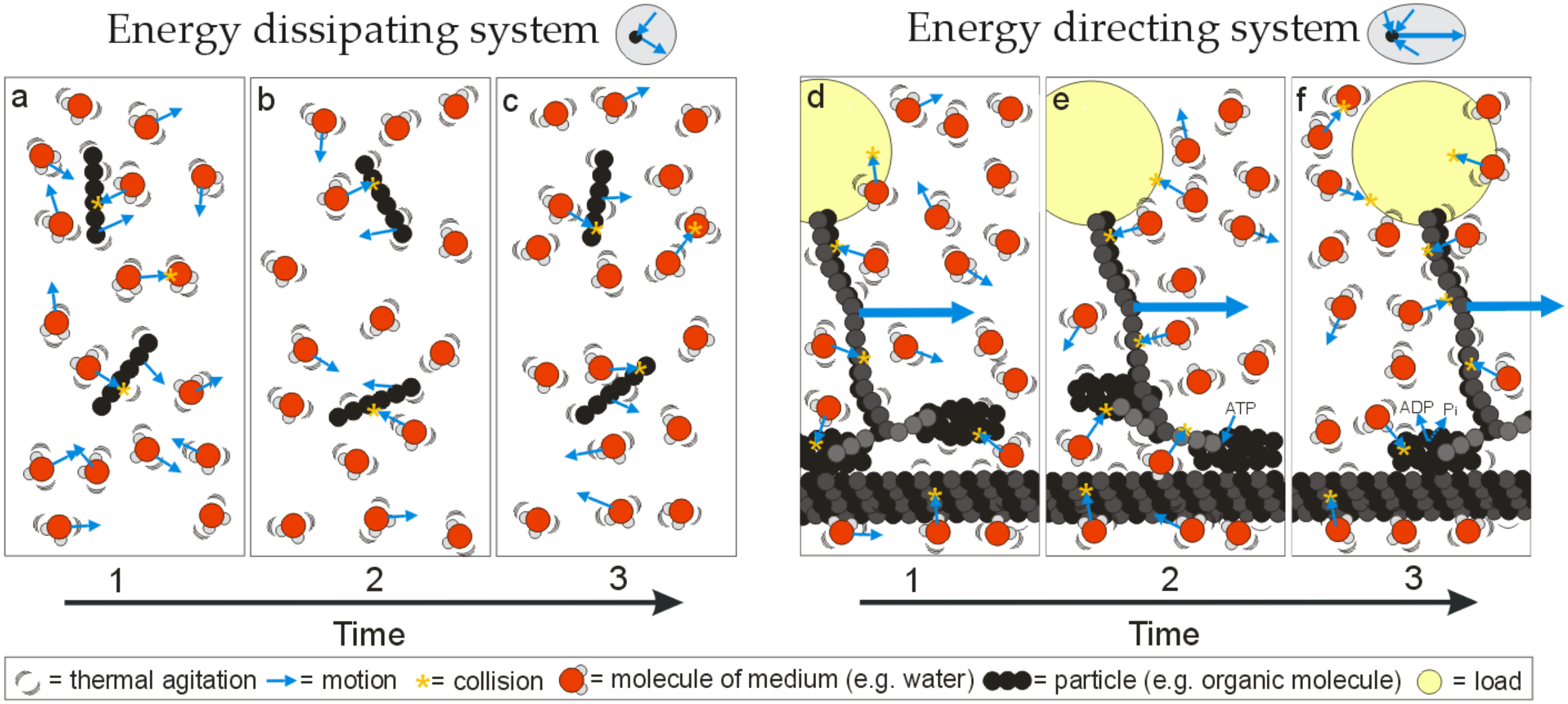




Despite being capable of backwards motion, these molecular engines all fundamentally exploit thermodynamic gradients to drive uniplanar conformation state changes, favoring motions that have directionality and can thus perform work

Energy redirection - random thermal motion converted to directional motion

Thermal energy dissipating *vs.* directing systems



Cartoon NOT TO SCALE

(e.g. water molecules are much smaller and more numerous!)

Simon Pierce (2023) Life's Mechanism. *Life,* 13(8): 1750. https://doi.org/10.3390/life13081750

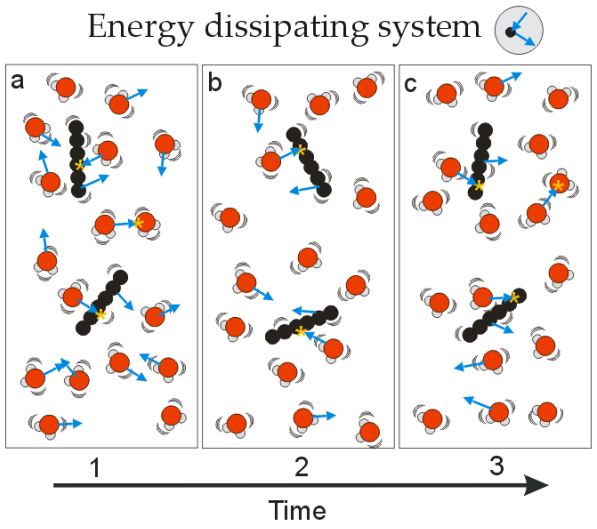
The Single Property Defining Living Systems

Changes in molecular conformation result in:

random thermal motion

no overall directionality

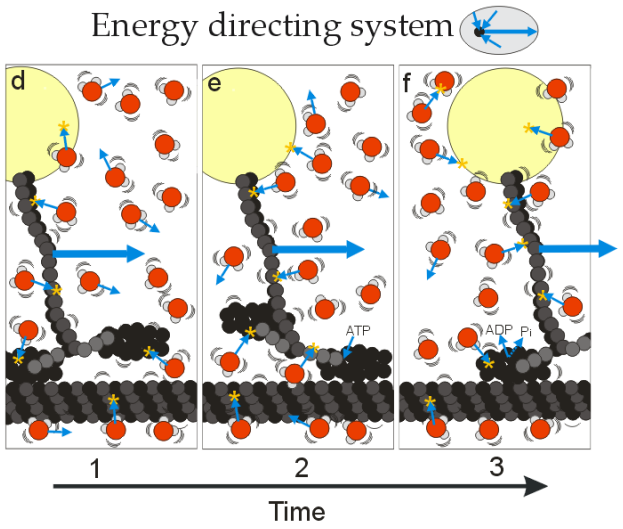
= no work



uniplanar thermal motion

unidirectional movement of system

= work

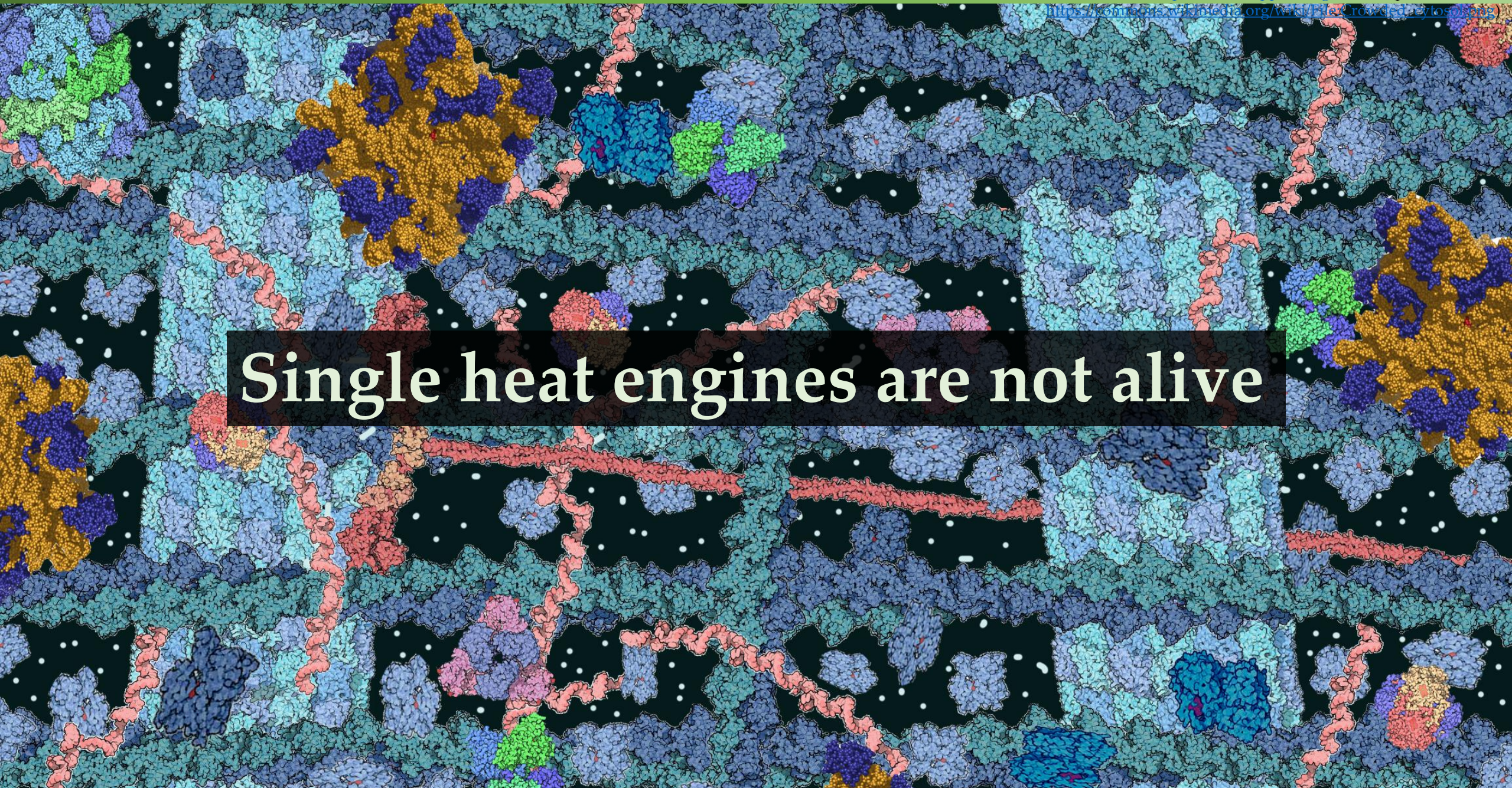


Simon Pierce (2023) Life's Mechanism. ***Life,*** **13(8): 1750.** https://doi.org/10.3390/life13081750

Work (creating negative entropy) is driven by positive entropy

A small mass of water is lifted (uphill) by a much larger mass running downhill (net entropy of the system is positive)

Life is a dynamic reaction network



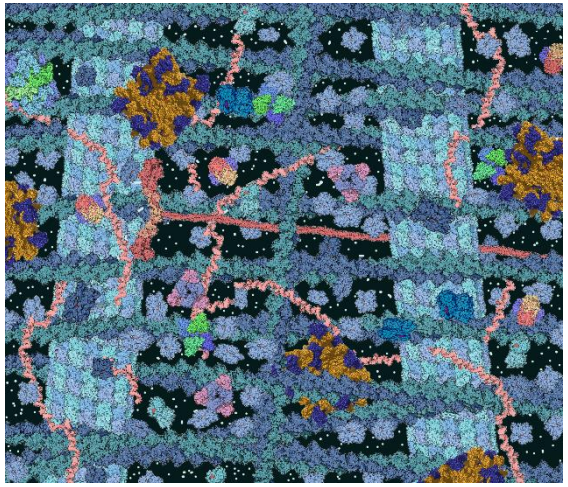
Picture of cytosol, showing microtubules (light blue), actin filaments (dark blue), ribosomes (yellow and purple), soluble proteins (light blue), kinesin (red), small molecules (white) and RNA (pink). David Goodsell https://ccsb.scripps.edu/goodsell/ (public domain; https://commons.wikimedia.org/wiki/File:Crowded_cytosol.png)

Single heat engines are not alive

Fundamental features of life

Key traits of life:

1. a self-regulating process (i.e. a self-sustaining kinetically stable dynamic reaction network; *sensu* Pross 2016),
2. **matter undergoes cyclic, uniplanar conformation state changes**,
3. **state changes convert thermodynamic disequilibria into directed motion,**
4. motion performs work,
5. work creates structure (reduces entropy locally) (*sensu* Schrödinger 1944)

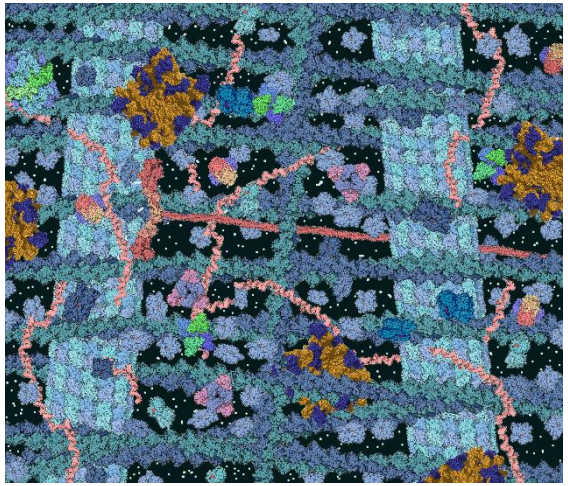


David Goodsell

A mechanistic definition of life

"Life is a self-regulating process whereby matter undergoes cyclic, uniplanar conformation state changes that convert thermodynamic disequilibria into directed motion, performing work that locally reduces entropy."

Simon Pierce (2023) Life's Mechanism. ***Life,*** **13(8): 1750. https://doi.org/10.3390/life13081750**

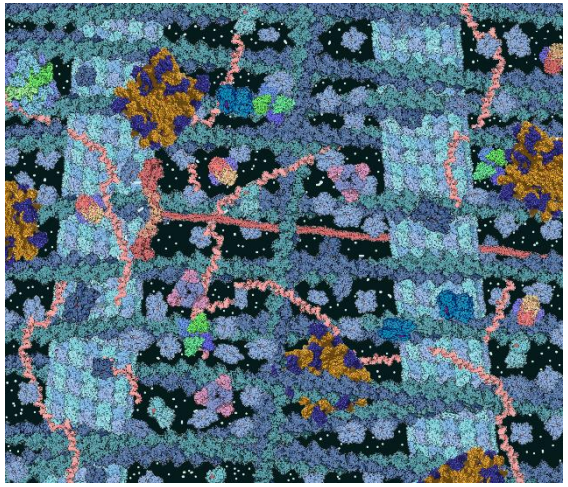


David Goodsell

A definition of a ‘living thing’

“A living thing is a structure comprising, at least in part, an autonomous network of units exploiting thermodynamic gradients to drive uniplanar conformation state changes that perform work.”

Simon Pierce (2023) Life’s Mechanism. ***Life,*** **13(8): 1750. https://doi.org/10.3390/life13081750**

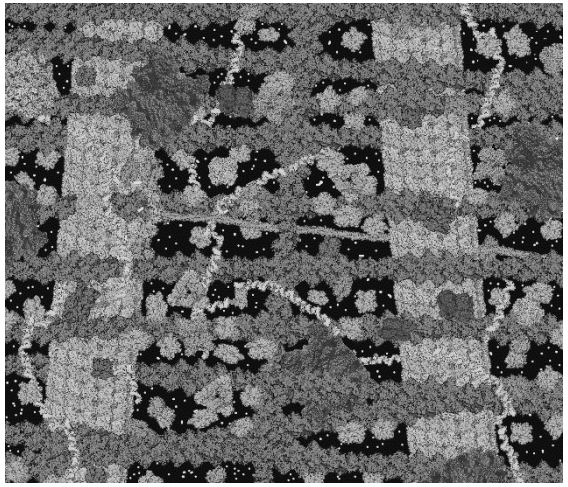


David Goodsell

Definitions of non-life and of death

"Lack of coordinated, directed motion in matter reflects a state of non-life, and where directed motion was previously evident in a molecular network, this lack essentially determines death."

Simon Pierce (2023) Life's Mechanism. ***Life,*** **13(8): 1750. https://doi.org/10.3390/life13081750**



David Goodsell

Reconciliation of typical exceptions to definitions of life

These are classic exceptions to definitions of life, reconsidered in light of the definition presented here:

Fire is a self sustaining reaction (but it increases entropy and is therefore not alive).

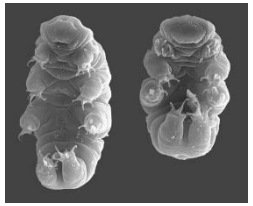
Crystals such as diamonds, table salt and snowflakes exhibit growth, structure and entropy decrease during formation, but crystallization results from compaction at high temperature, precipitation from a solution, or by freezing of vapour, respectively, rather than being products of an autonomous and integrated network of heat engines. [∴ not alive].

Cyclones show structure and are themselves single heat engines, but structure emerges from convection and pressure gradients rather than uniplanar conformation state changes within the matter from which they are composed. They do not form stable autonomous networks. [∴ not alive].

Simon Pierce (2023) Life's Mechanism. *Life,* **13(8): 1750. https://doi.org/10.3390/life13081750**

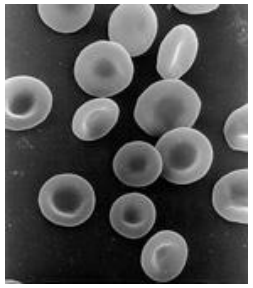
Reconciliation of typical exceptions to definitions of life

Frozen bacteria or **frozen tardigrades** are alive because metabolism (working on heat engine principles) proceeds, albeit extremely slowly, with cell components in a protected state known as cryptobiosis. [∴ alive].



Willow Gabriel, Goldstein Lab; CC BY-SA 2.5 DEED

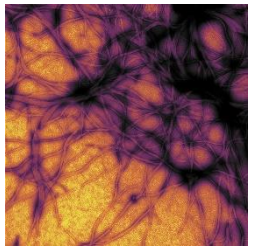
Red blood cells (erythrocytes) actively metabolise to maintain the integrity and function of the cell membrane and of haemoglobin for oxygen transport; the cytoskeleton (and ratcheting motor enzymes) is essential for this. Mammal erythrocytes have no nucleus (thus no synthesis and replication) and are 'alive but senescent'. [∴ alive].



Simon Pierce (2023) Life's Mechanism. ***Life,*** **13(8): 1750. https://doi.org/10.3390/life13081750**

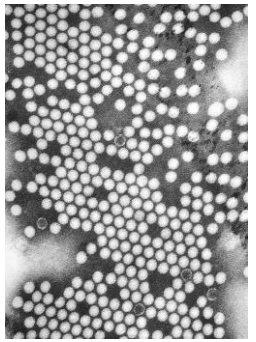
Reconciliation of typical exceptions to definitions of life

Prions (misfolded prion protein) have biological origins and appear to replicate, but are structurally rigid (the conformation changes occurring during their formation are akin to an irreversible collapse and crumpling), and 'replication' is alteration in the state of existing protein, having little to do with true replication (i.e., production of new complex structures from simpler materials following information inherited across generations). [∴ not alive].



NIAID/Roger Moore;
CC Attribution 2.0 generic

Viruses: in their free state they are aggregates of molecules (a non-living state), but when they encounter cell membranes and are then intimately incorporated into metabolic machinery, they actively participate in the directed motion network (share the living state of the cell), which reduces entropy by converting simple resources into more complex copies of virus particles. [Non-life? Viruses are not self-regulating and the living state is that of the cell].



PD-USGov-HHS-CDC

Dead person, live organs. Human bodies are a mosaic of life and non-life, meaning that medical/legal death of the person (the entire organism) can be ascribed based on the irreversible failure of one vital organ (heart or brain; *sensu* the Uniform Determination of Death Act, USA) despite other organs being alive. In the case of live organ transplants, a living heart (with cells demonstrating active and integrated heat engines) removed from a donor with a dead brain (in which heat engine integration is quenched) is congruent with the current definition of life.
[∴ alive]

Korozia45
CC BY-SA 4.0 Deed

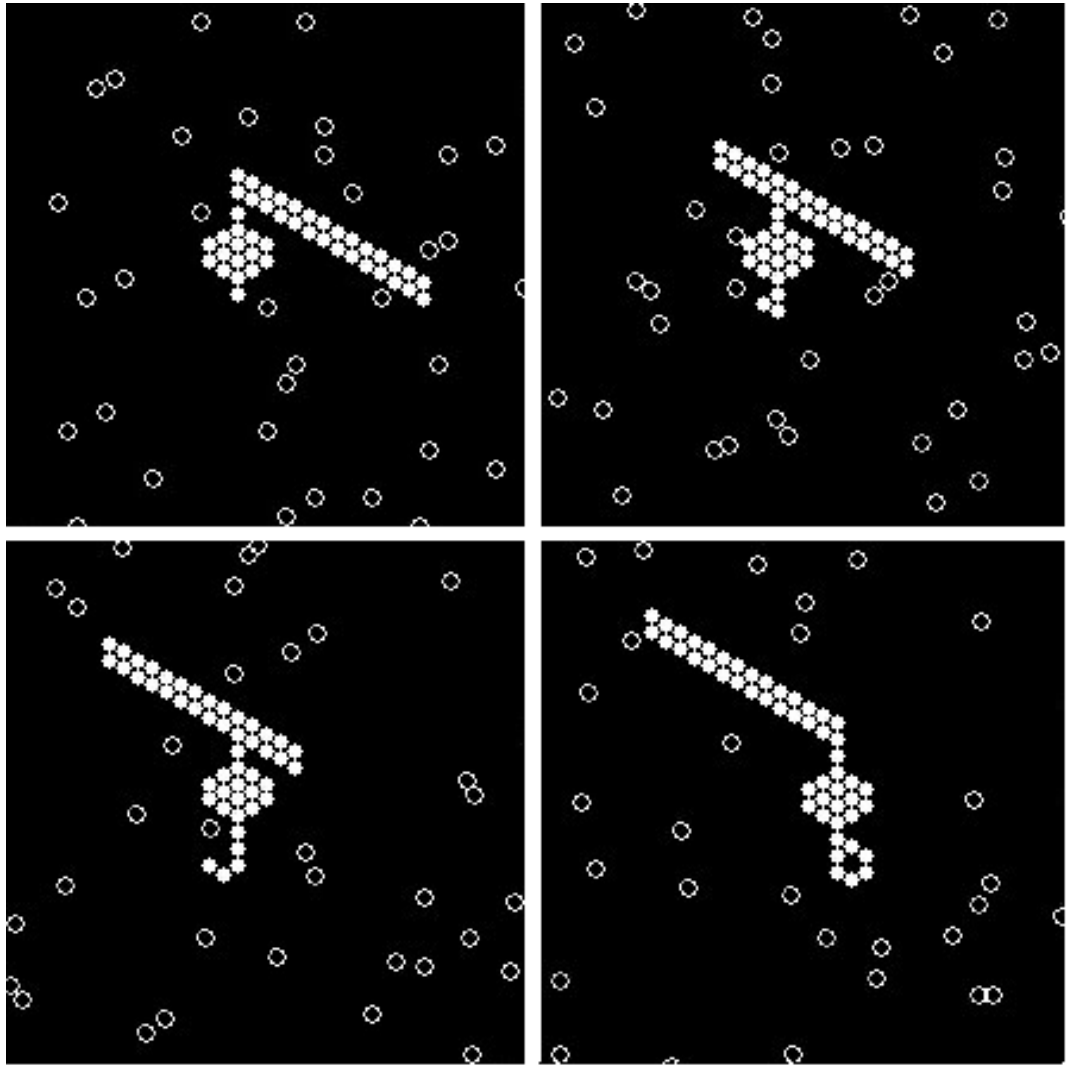
Simon Pierce (2023) Life's Mechanism. ***Life,*** **13(8): 1750. https://doi.org/10.3390/life13081750**

Artificial life (ALife)

A universal constructor in the DigiHive environment. The constructor builds a ring shape according to its description encoded in an information string. Rafal s76; CC BY-SA 3.0 Deed

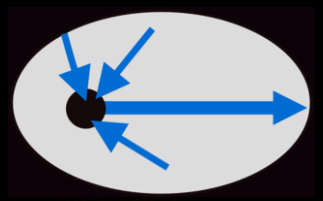
"If an artificial network of devices were able to use a heat engine network to reduce entropy, create order and subsequently become self-regulating and self-replicating, then it would be considered alive."

"Many biological organisms are composed of structures operating on different principles over vastly different scales, from molecules, cells, tissues, to organs, integrated to allow self-sufficiency and survival of the individual … One can conceive of a 'soft' ALife system (software) managing and feeding back with a 'hard' ALife system (robotics) to create a self-sustaining and self-governing physical structure. This is conceptually similar to the mechanics of a large multicellular organism functioning under the influence of biochemistry and instructions operating at much smaller physical scales."



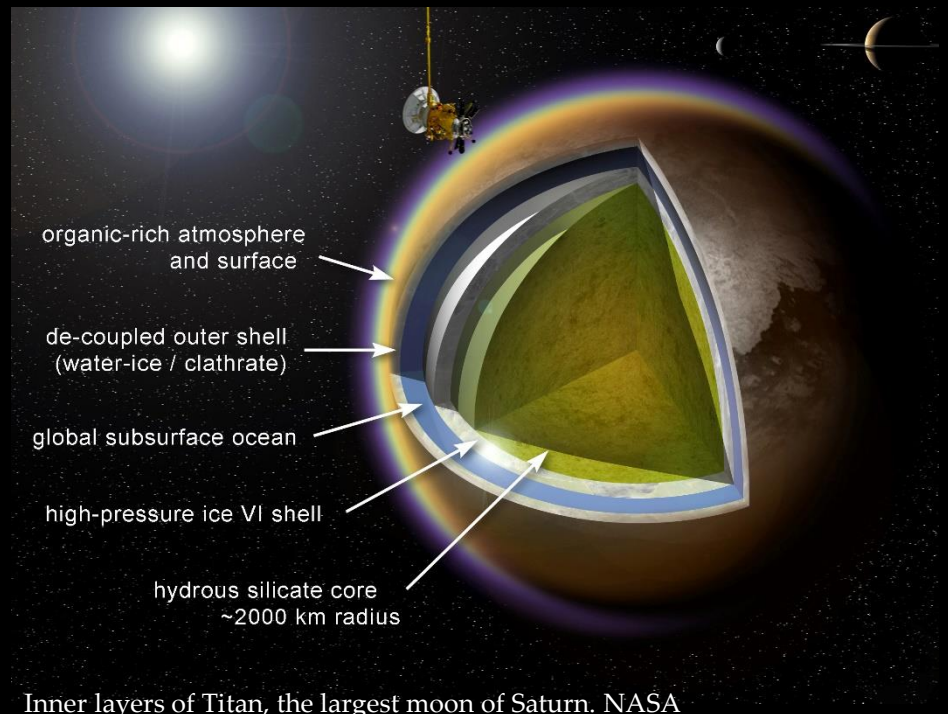
Simon Pierce (2023) Life's Mechanism. ***Life,*** **13(8): 1750. https://doi.org/10.3390/life13081750**

Random to directed thermal motion

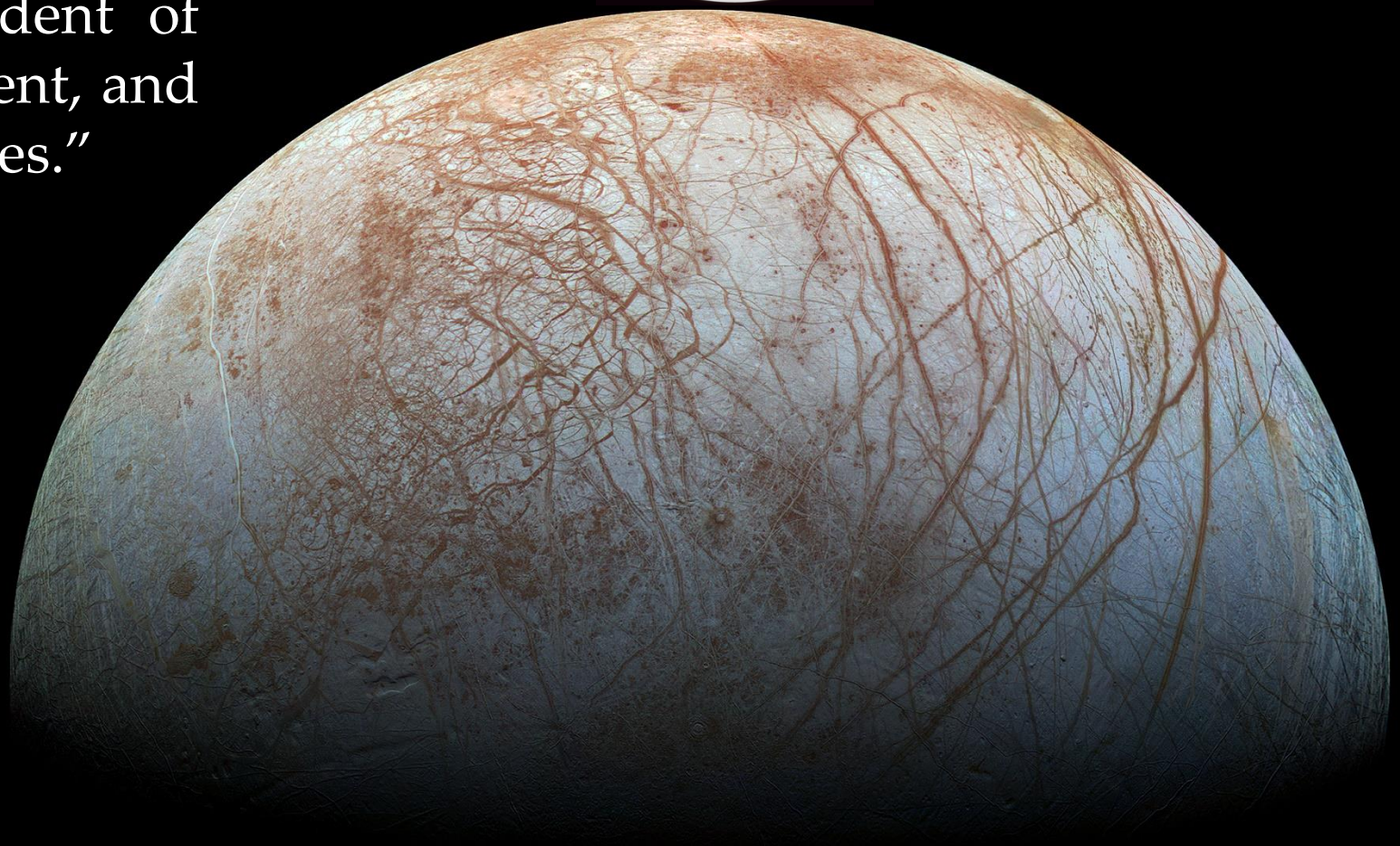


"These principles are independent of any specific chemical environment, and can be applied to other biospheres."

Simon Pierce (2023) Life's Mechanism. ***Life,*** **13(8): 1750.**
https://doi.org/10.3390/life13081750



Inner layers of Titan, the largest moon of Saturn. NASA

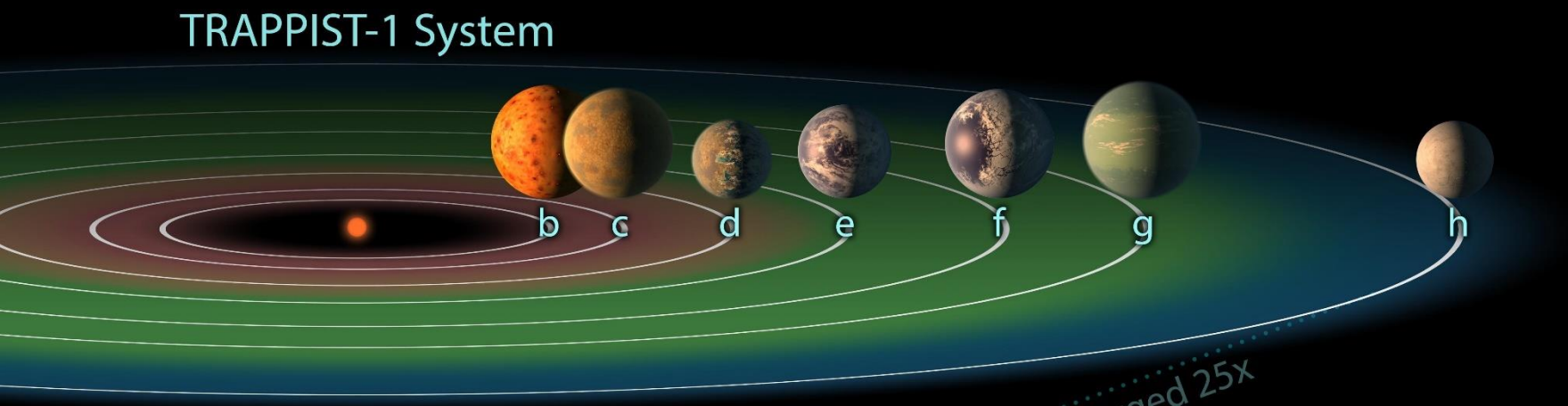


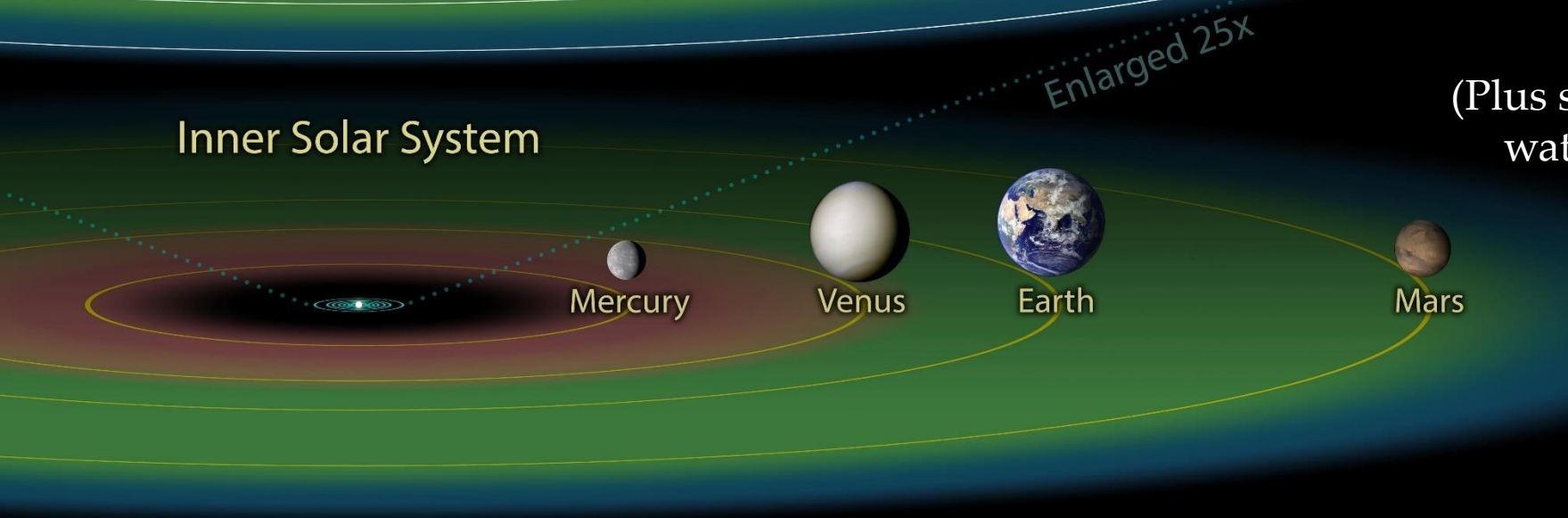
Surface of Jupiter's icy moon Europa; NASA / Jet Propulsion Lab-Caltech / SETI Institute

Life Throughout the Universe

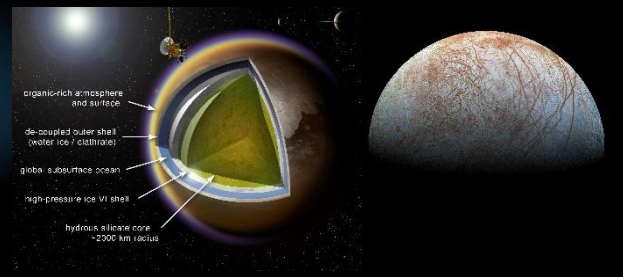
"Life's main requirement is the thermal bath and increasing entropy of the universe, and thermal agitation is particularly strong in the regions of the universe close to stars. Many star systems are now known to include planets with an appropriate temperature such that liquid water and complex molecules almost certainly exist."

Simon Pierce (2023) Life's Mechanism. ***Life,*** **13(8): 1750.** https://doi.org/10.3390/life13081750



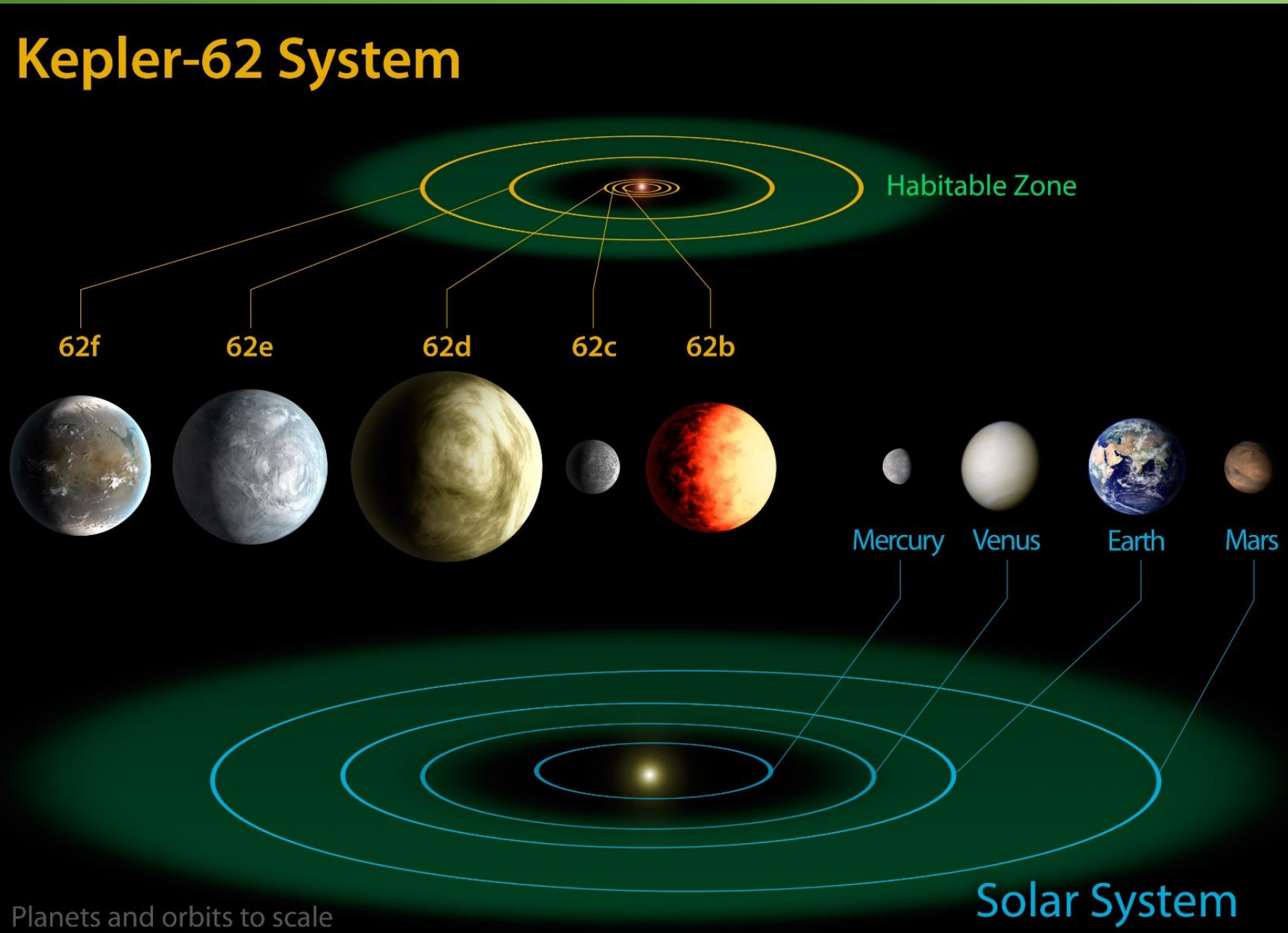


(Plus situations outside the 'surface liquid water' habitable zone where thermally-agitated liquid media can exist!)

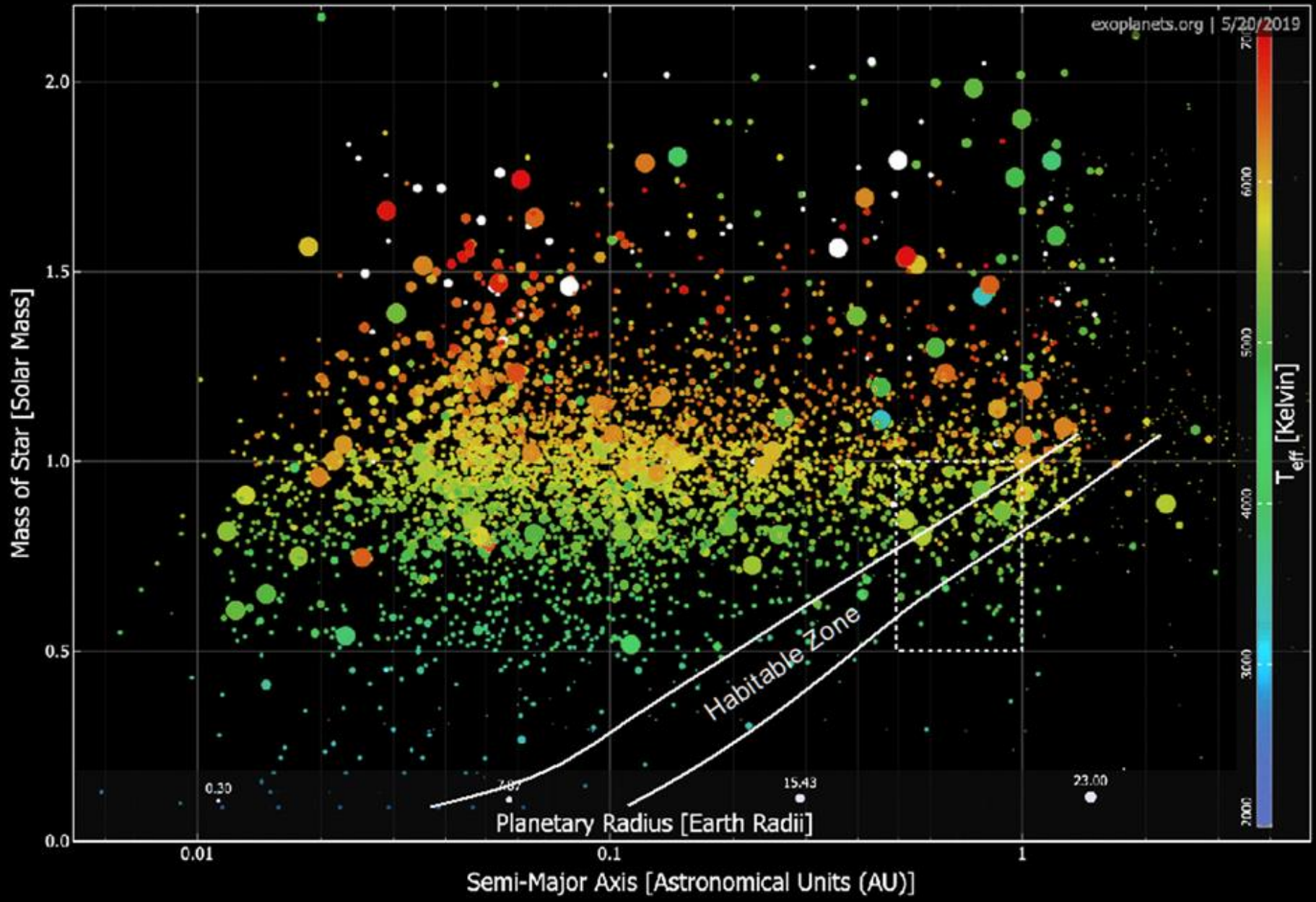


Life Throughout the Universe

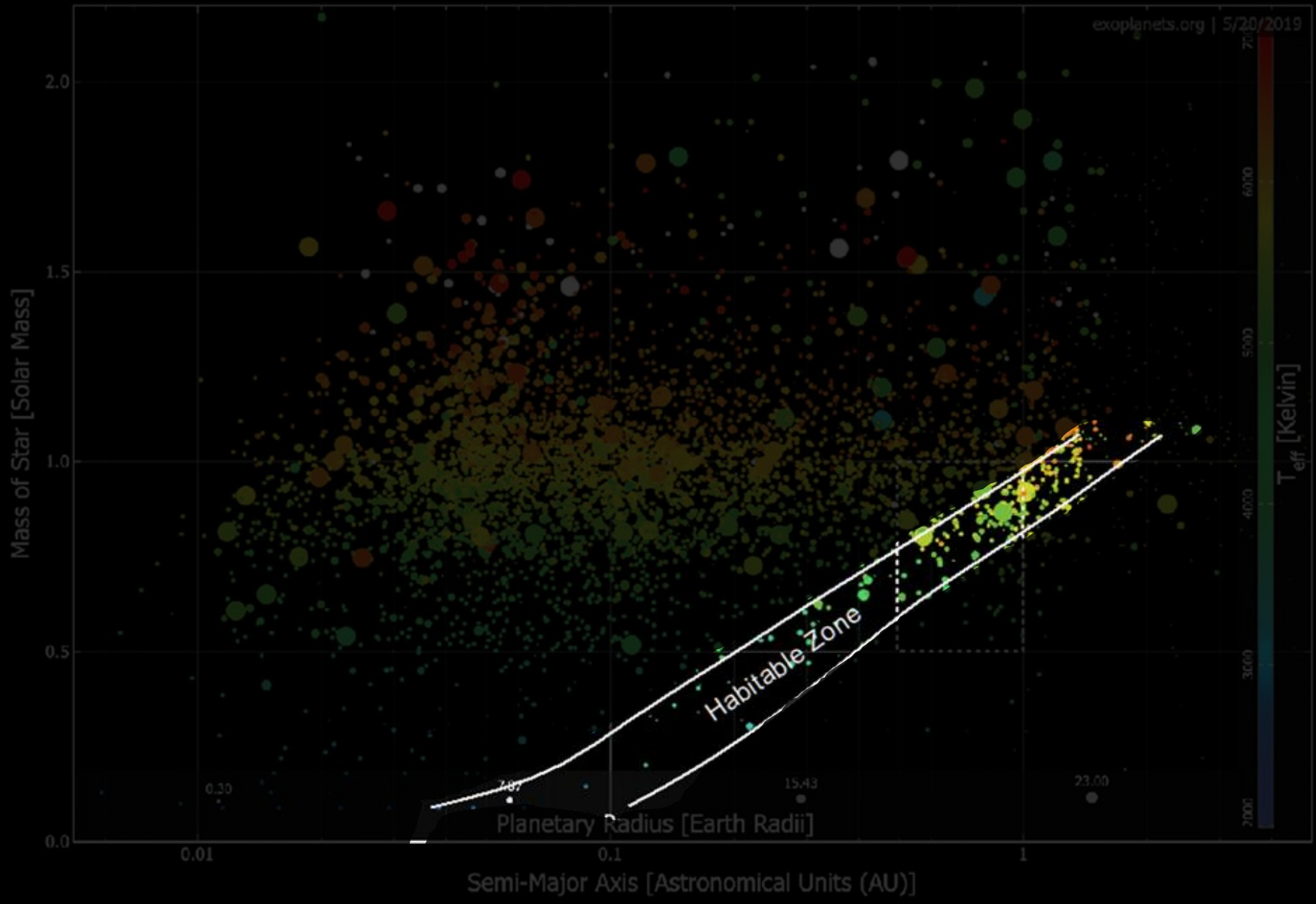
NASA Ames/JPL-Caltech (Public Domain)



Life Throughout the Universe

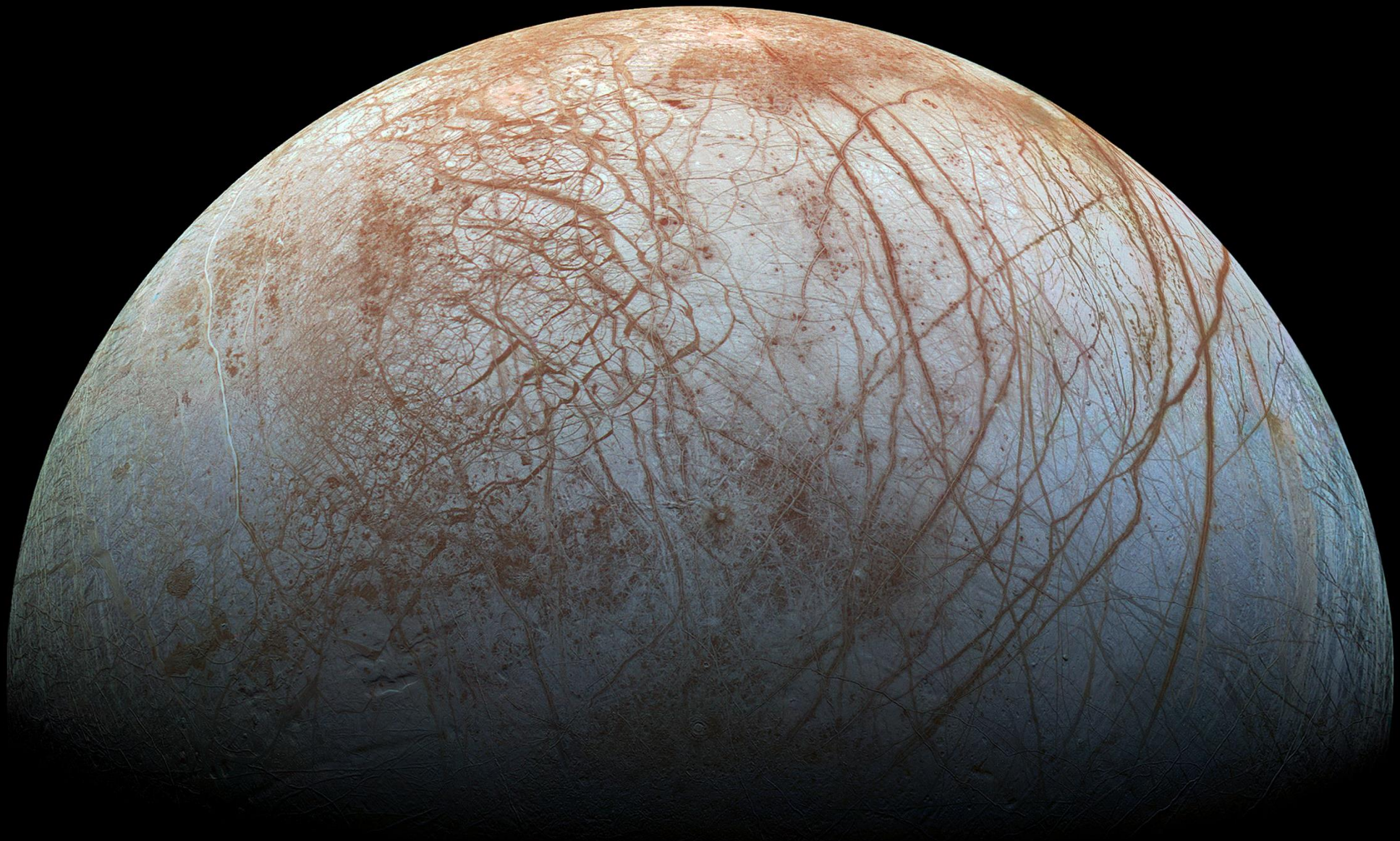


What do the surfaces of habitable alien worlds look like?



What do the surfaces of habitable alien worlds look like?

What do the surfaces of habitable alien worlds look like?



Surface of Jupiter's icy moon Europa; NASA / Jet Propulsion Lab-Caltech / SETI Institute

What do the surfaces of habitable alien worlds look like?

Thomas Moran 1872 (Public Domain)

What do the surfaces of habitable alien worlds look like?

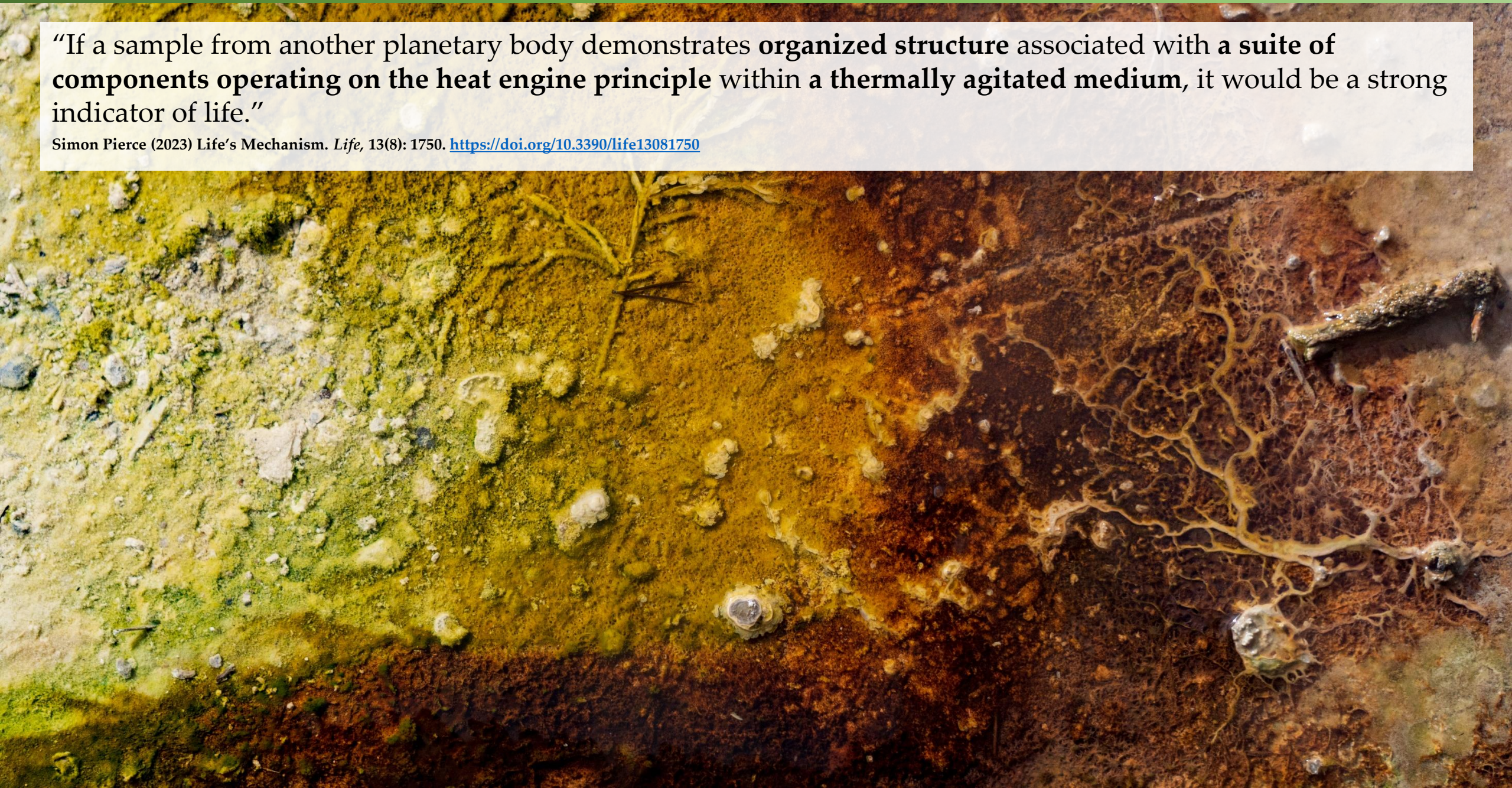
What do the surfaces of habitable alien worlds look like?

What do the surfaces of habitable alien worlds look like?

What do the surfaces of habitable alien worlds look like?

Filamentous bacteria at Mammoth Hot Springs, by Yellowstone National Park (Public Domain)

Identifying life



Closeup of a color gradient resulting from different bacteria accumulating in different temperature zones of a thermal pool. Beryl Spring in Yellowstone National Park. Aleksomber

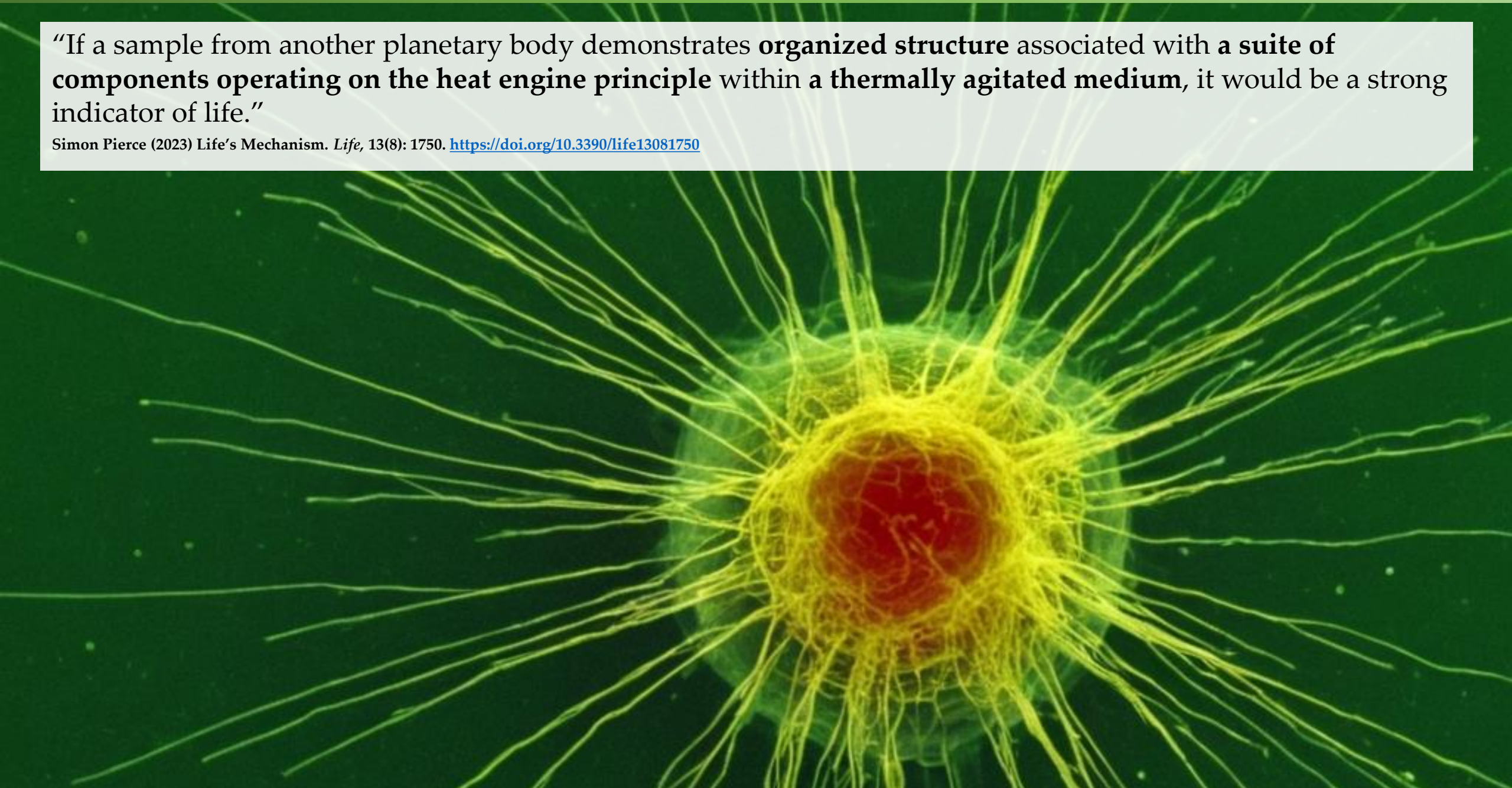
"If a sample from another planetary body demonstrates **organized structure** associated with **a suite of components operating on the heat engine principle** within **a thermally agitated medium**, it would be a strong indicator of life."

Simon Pierce (2023) Life's Mechanism. ***Life,*** **13(8): 1750. https://doi.org/10.3390/life13081750**

Identifying life

"If a sample from another planetary body demonstrates **organized structure** associated with **a suite of components operating on the heat engine principle** within **a thermally agitated medium**, it would be a strong indicator of life."

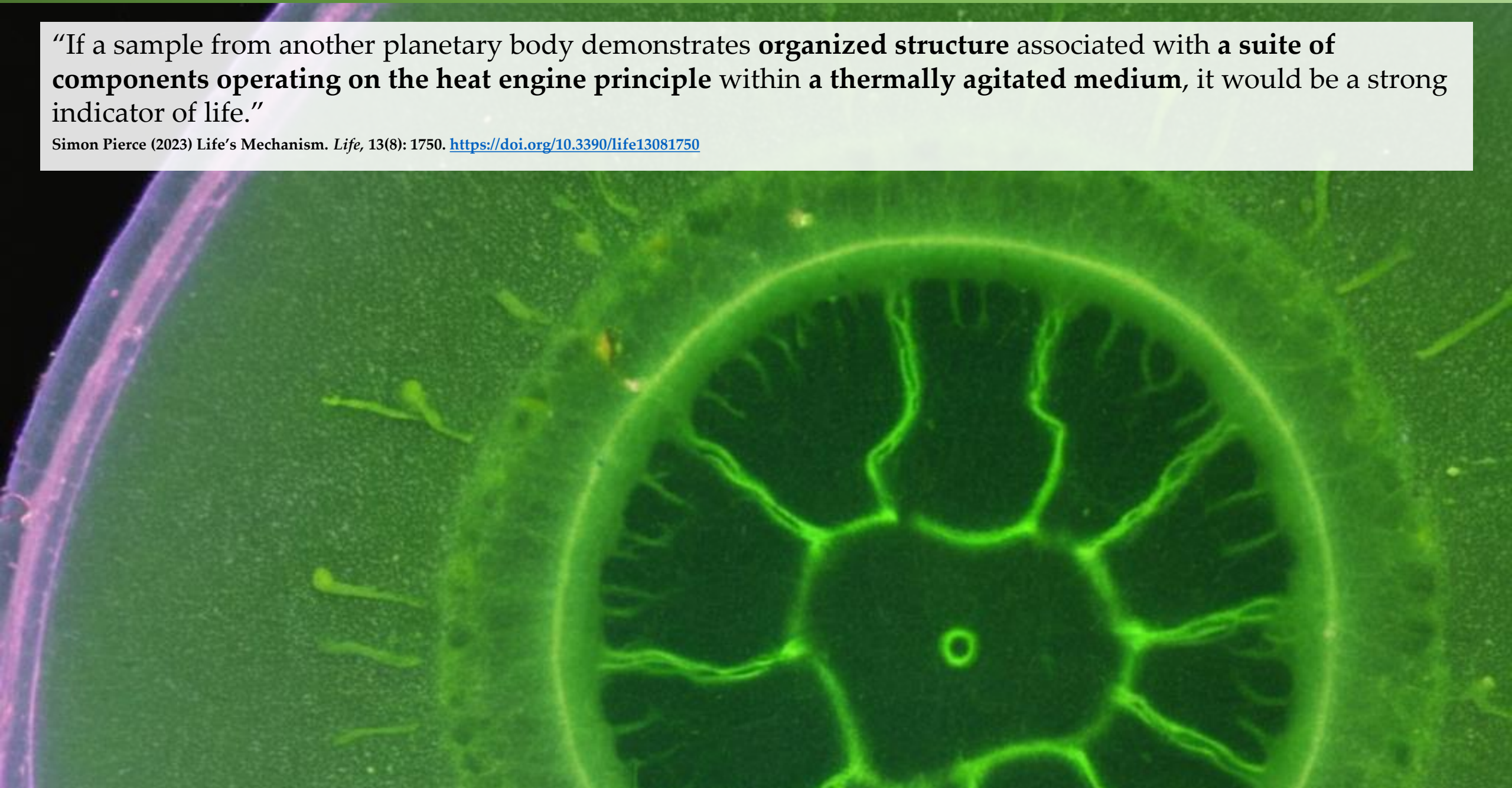
Simon Pierce (2023) Life's Mechanism. ***Life,*** **13(8): 1750.** https://doi.org/10.3390/life13081750



Identifying life

"If a sample from another planetary body demonstrates **organized structure** associated with **a suite of components operating on the heat engine principle** within **a thermally agitated medium**, it would be a strong indicator of life."

Simon Pierce (2023) Life's Mechanism. ***Life,*** **13(8): 1750.** https://doi.org/10.3390/life13081750



Identifying life

"If a sample from another planetary body demonstrates **organized structure** associated with **a suite of components operating on the heat engine principle** within **a thermally agitated medium**, it would be a strong indicator of life."

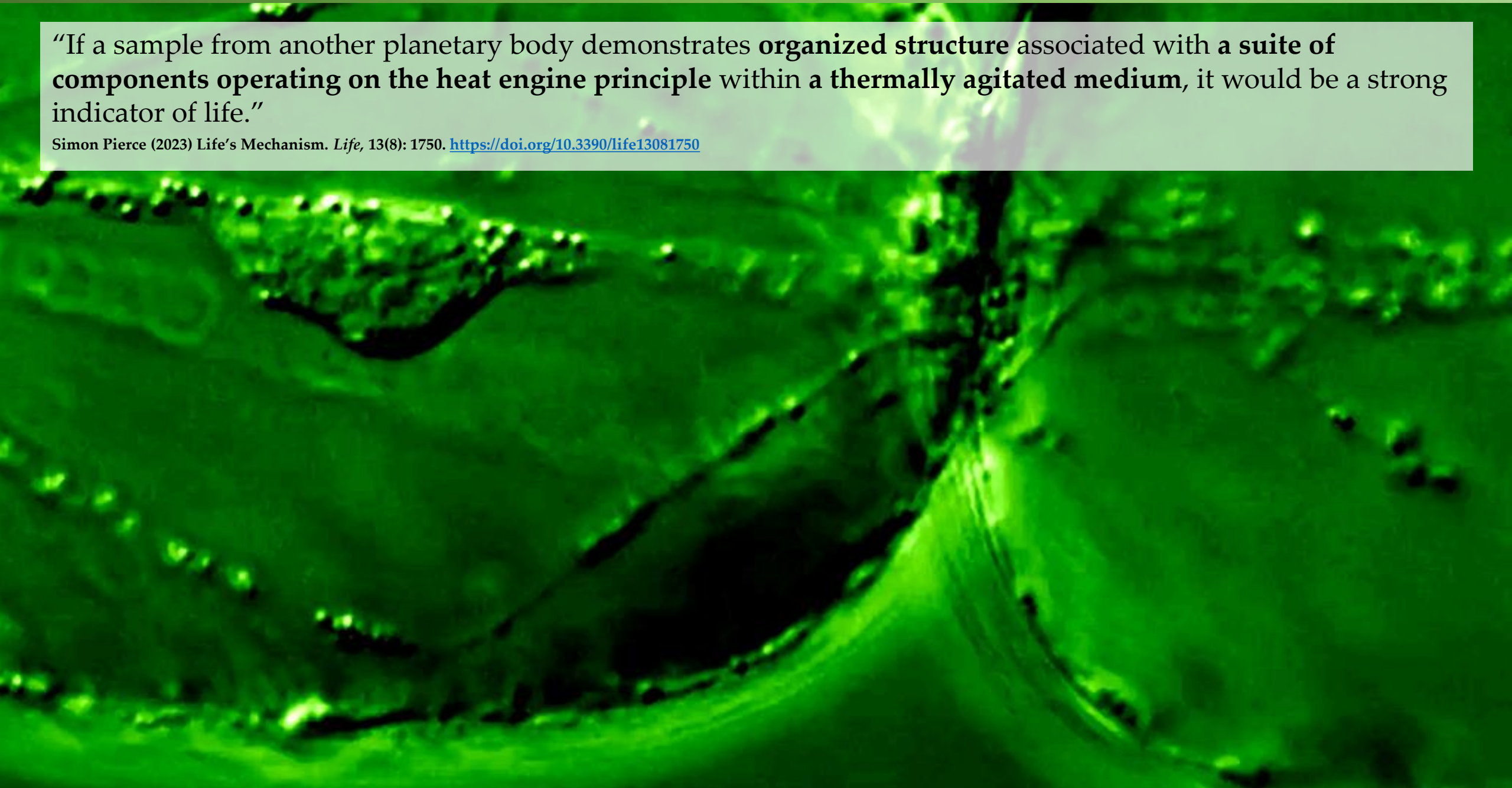
Simon Pierce (2023) Life's Mechanism. ***Life,*** **13(8): 1750.** https://doi.org/10.3390/life13081750

Identifying life

"If a sample from another planetary body demonstrates **organized structure** associated with **a suite of components operating on the heat engine principle** within **a thermally agitated medium**, it would be a strong indicator of life."

Simon Pierce (2023) Life's Mechanism. ***Life,*** **13(8): 1750.** https://doi.org/10.3390/life13081750

Identifying life



Movement of organelles in *Tradescantia* stamen hair cells 2012 Heiti Paves
(Modified by altering the contrast, luminosity and hue, and by cropping) CC BY-SA 4.0 Deed

"If a sample from another planetary body demonstrates **organized structure** associated with **a suite of components operating on the heat engine principle** within **a thermally agitated medium**, it would be a strong indicator of life."

Simon Pierce (2023) Life's Mechanism. ***Life,*** **13(8): 1750. https://doi.org/10.3390/life13081750**

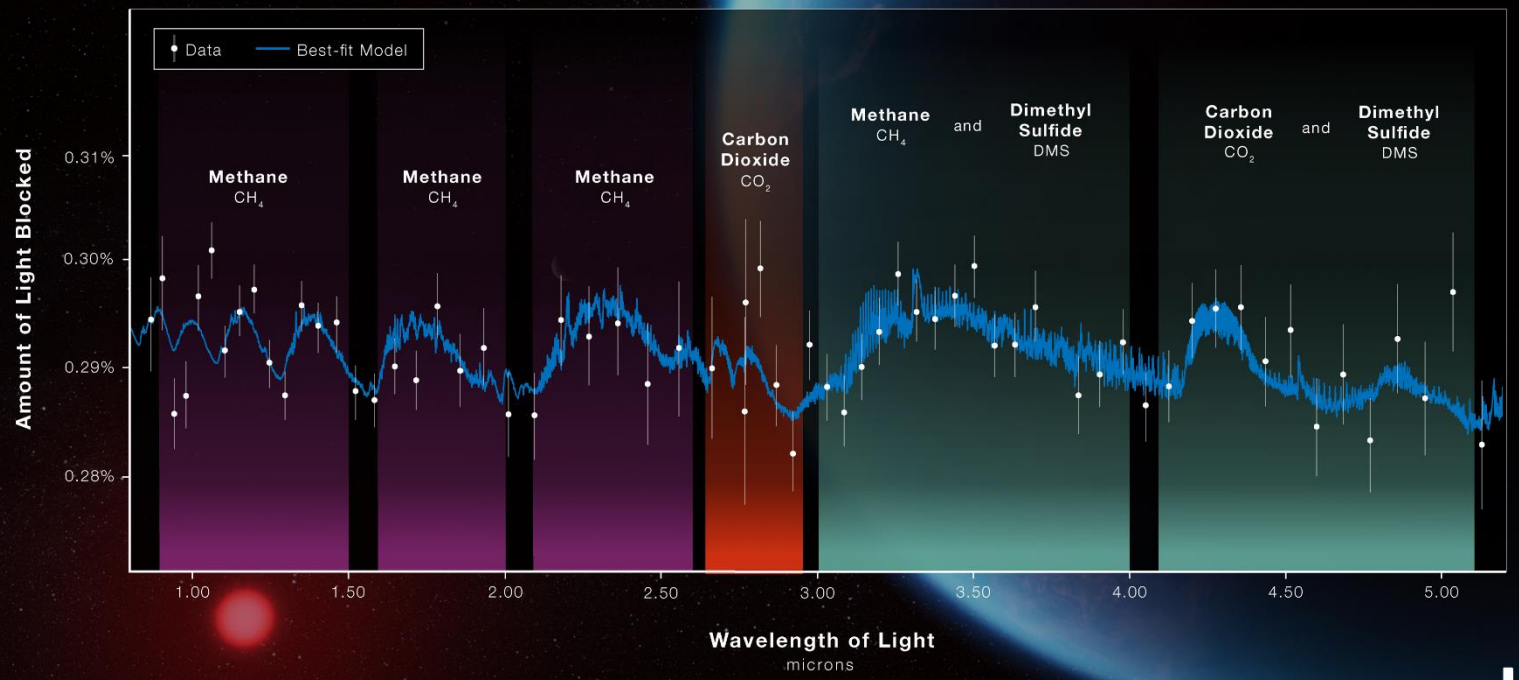
Identifying life

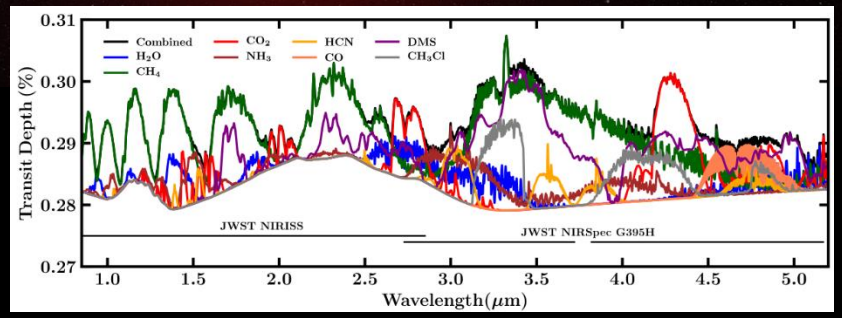
Spectra of K2-18 b, obtained with Webb's NIRISS (Near-Infrared Imager and Slitless Spectrograph) and NIRSpec (Near-Infrared Spectrograph) displays an abundance of methane and carbon dioxide in the exoplanet's atmosphere, as well as a possible detection of a molecule called dimethyl sulfide (DMS).Illustration: NASA, ESA, CSA, Ralf Crawford (STScI), Joseph Olmsted (STScI) Science: Nikku Madhusudhan (IoA)(public domain)

EXOPLANET K2-18 b

ATMOSPHERE COMPOSITION

NIRISS and NIRSpec (G395H)

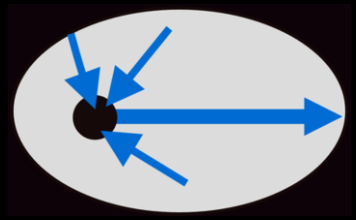




WEBB SPACE TELESCOPE

Principles emerging from the definition of life:

- Chemical traces or fossilized structures will not reveal the action of 'uniplanar' heat engine networks (they are suggestive rather than conclusive).
- Conclusive identification of life on other planetary bodies requires demonstration of how molecules move (**random *vs.* directional motion**) within a thermally-agitated medium



Madhusudhan N. et al. 2023 ApJL 956 L13
https://iopscience.iop.org/article/10.3847/2041-8213/acf577; CC BY-SA 4.0 Deed

How rare are civilisations?

NASA astronaut Scott Kelly took this photograph of a moonrise over the western united states.
Scott Kelly/NASA (public domain)

For 4.56 billion years Earth has occupied a habitable zone and for ~4 billion years it has hosted microbial life, but for the vast majority (~99.998 %) of it's existence it has lacked a technological civilisation

Evidence for human culture ~80,000 y ago
www.pnas.org/doi/full/10.1073/pnas.1204213109

From the peer-reviewed paper:

Life's Mechanism

the self-regulating conversion of thermodynamic disequilibria into directed motion

Simon Pierce (2023) Life's Mechanism. ***Life*****, 13(8): 1750.** https://doi.org/10.3390/life13081750

Abstract: The multifarious internal workings of organisms are difficult to reconcile with a single feature defining a state of 'being alive'. Indeed, definitions of life rely on emergent properties (growth, capacity to evolve, agency) only symptomatic of intrinsic functioning. Empirical studies demonstrate that biomolecules including ratcheting or rotating enzymes and ribozymes undergo repetitive conformation state changes driven either directly or indirectly by thermodynamic gradients. They exhibit disparate structures, but govern processes relying on directional physical motion (DNA transcription, translation, cytoskeleton transport) and share the principle of repetitive uniplanar conformation changes driven by thermodynamic gradients, producing dependable unidirectional motion: 'heat engines' exploiting thermodynamic disequilibria to perform work. Recognition that disparate biological molecules demonstrate conformation state changes involving directional motion, working in self-regulating networks, allows a mechanistic definition: *life is a self-regulating process whereby matter undergoes cyclic, uniplanar conformation state changes that convert thermodynamic disequilibria into directed motion, performing work that locally reduces entropy.* 'Living things' are structures including an autonomous network of units exploiting thermodynamic gradients to drive uniplanar conformation state changes that perform work. These principles are independent of any specific chemical environment, and can be applied to other biospheres.

Acknowledgments: The author thanks G. Wilson Fernandes (Department of General Biology, Federal University of Minas Gerais) for encouraging the development of these ideas via an invitation to talk to the Postgraduate Programme in Ecology, Conservation and Wildlife on 16 November 2016 (Programa de Pós-Graduação em Ecologia, Conservação e Manejo de Vida Silvestre Ecologia Evolutiva e Biodiversidade, Departamento de Biologia Geral, Universidade Federal de Minas Gerais, Belo Horizonte, MG, Brazil).