Life without organic molecules – exploring the boundaries of life

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We are familiar with the notion of carbon-based life forms, but are there alternatives? In this article, I describe an approach to build a living machine from engineering materials that lacks any biochemistry but uses engineering methods to live. In devising this self-replicating machine, we explore broader scientific notions of what life might be and how it might be realized, rather than being limited to what it is on Earth.

An adequate definition of life has been notoriously difficult to capture. The transition at some point in Earth's evolution from non-life to life was not a flip across a crisp boundary but a slither through a fuzzy one. Perhaps it is not altogether surprising therefore that the concept of life is *so* slippery. Indeed, one severe handicap confronting us is that we only have experience of life on a single world – unlike the laws of physics and chemistry which are universal, biology on Earth is, by definition, more parochial. Nevertheless, it is the business of the astrobiology community to consider the prospect of life elsewhere. Hitherto, this investigation has been premised on searching for extraterrestrial habitats that resemble terrestrial habitats, albeit the more extreme of Earth's habitats. For instance, my group is currently figuring out how to design and build a small penetrator to impact into the 'tiger stripes' near the south pole of Enceladus, a moon of Saturn, from which plumes of water are emanating into space. We have been developing an astrobiology instrument package and are drawing up a biomimetic strategy to target the subsurface ocean based on how animals track odours to find sources of food or mates. Our current detection strategy assumes that extraterrestrial life will be similar to that associated with terrestrial deep-sea vents and based on nucleic acids/proteins within a liquid water medium.

Can we gain a handle on more generalized forms of life that are not enslaved to a particular biochemistry? There is the discipline of artificial life that simulates aspects of life on a computer – the primary aspect explored is evolution (the bane of synthetic biology). This has already spawned practical applications – evolutionary algorithms are used to solve complex optimization problems in engineering. The earliest foray into artificial life was initiated by John von Neumann. He was one of the great mathematicians of the 20th century – one of the so-called *Hungarian Martians* that included von Karman, Wigner, Teller, Polya, Kemeny, Erdos and Szilard, luminaries all – who explored the logic of life, building on ideas from Alan Turing, the British mathematician who single-handedly invented the concept of the computer. von Neumann's premise was that the unique characteristic of life is the ability to self-replicate. This single capability implies a host of properties including metabolism supported by a supply of materials and energy, and the capacity to evolve due to errors in self-replication. Turing's genius was to recognize that a single machine – a universal computing machine – could perform any logical task encoded in an algorithm. Today we take this for granted, but prior to Turing, every physical machine was dedicated to a specific task. von Neumann extended this idea to a universal constructing machine – a machine that can build anything given the appropriate programme of instructions, physical materials and components, and an energy supply. A self-replicating machine is merely a universal constructor programmed with the necessary instructions to build a copy of itself. von Neumann's insight was to realize that the programme of instructions must be read and executed to build the copy (translation of DNA) but must also be copied without execution for the new machine (translation of DNA). von Neumann's insights preceded the discovery of the structure of DNA by Watson, Crick and Franklin. There are, therefore, two major components to a self-replicating machine – a universal constructor (proteins) and a universal computer (DNA). Of course, the RNA world assumes that RNA implemented both functions in the last universal common ancestor (LUCA) but these functions are distinct.

Functionality	Lunar-derived Material
Tensile structures	Wrought iron Aluminium
Compressive structures	Cast iron Aluminium Regolith/binder
Elastic structures	Steel springs/flexures Silicone elastomers
Hard structures	Alumina
Thermal conductor straps	Fernico (e.g. kovar) Nickel
Thermal insulation	Glass (SiO_2 fibre) Ceramics such as SiO_2
High thermal tolerance	Tungsten Alumina
Electrical conduction wire	Fernico (e.g. kovar) Nickel Aluminium
Electrical insulation	Glass Ceramics (SiO_2, Al_2O_3 and TiO_2) Silicone plastics Silicon steel for motors
Active electronics devices (vacuum tubes)	Kovar Nickel Tungsten Fused silica glass
Magnetic materials	Cobalt-ferrite Silicon steel Permalloy
Sensory transducers	Resistance wire Quartz Selenium
Optical structures	Polished nickel Fused silica glass
Lubricants	Silicone oils Water
Adhesives	Silicone elastomer/gel
Combustible fuels	Oxygen Hydrogen

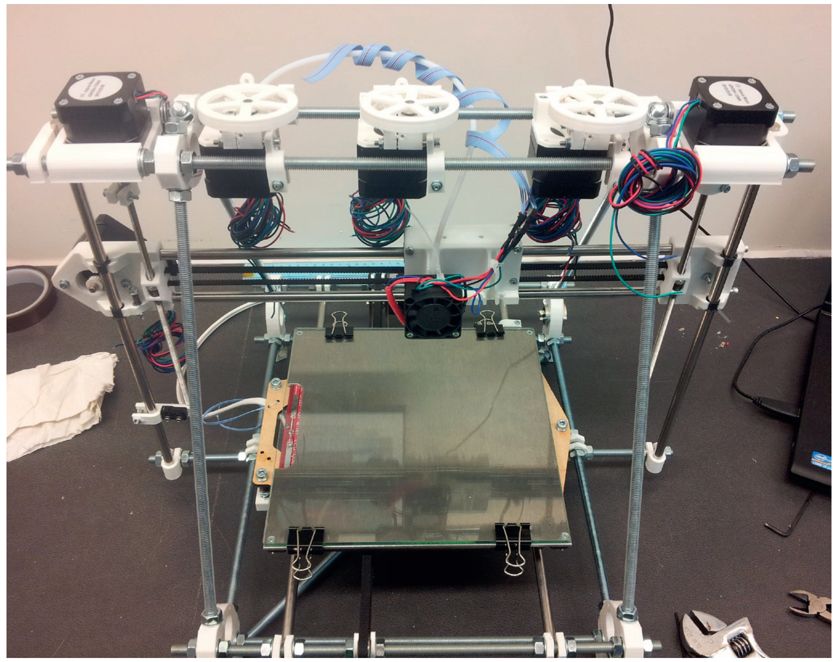
Table 1. Minimal list of functional materials derivable from the Moon
We have defined an entire metabolism complete with recycling loops to resemble a homeostatic system – an industrial ecology is implied within a self-replicating machine to minimize waste of material and energy.

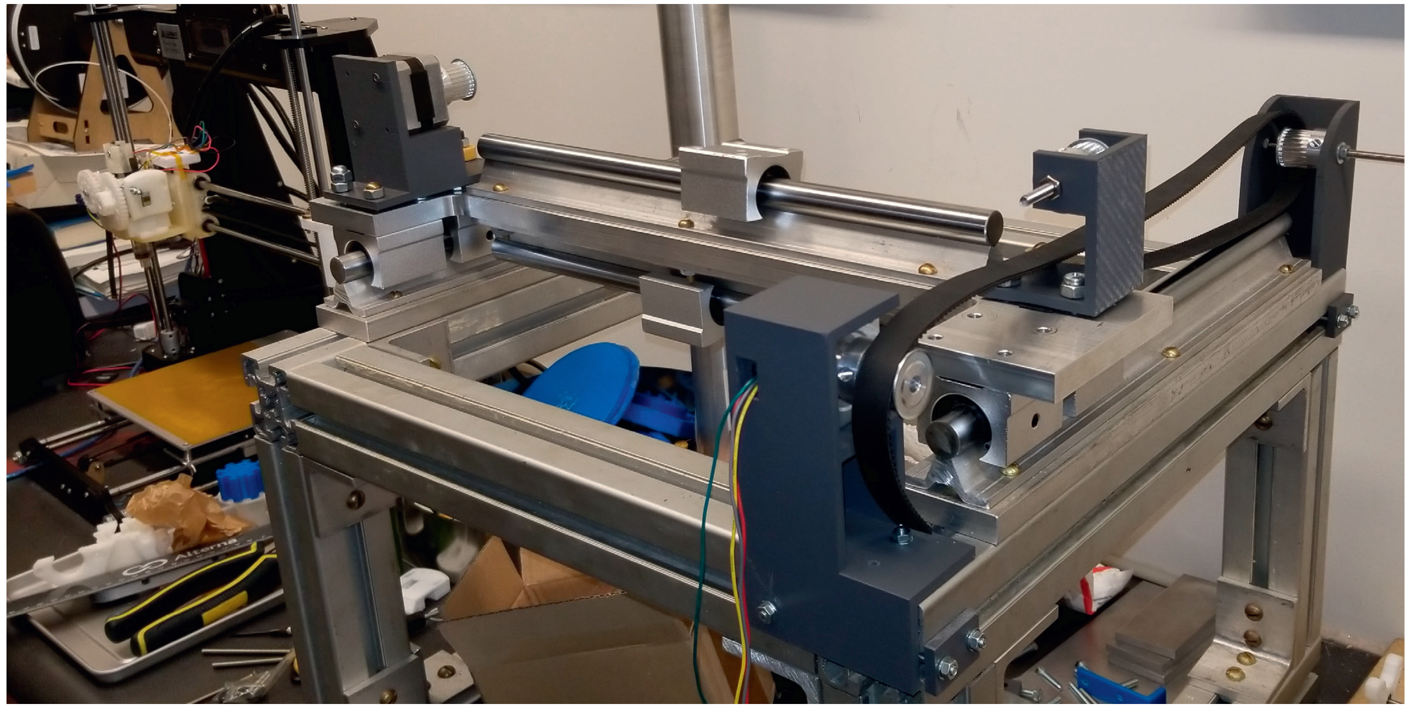
I have been in the process of converting these abstract concepts into a physical machine – effectively, a living machine that is divorced from biochemistry and explores the limits of life. My self-replicating machine concept will be designed to survive on the Moon where no pre-existing biosphere exists and is physically isolated from the Earth's biosphere.

Metabolic activity – the provision and use of energy and the synthesis of biological tissue – appears to be the central linchpin in biochemistry. An archetypal example might be the Krebs cycle, which describes aerobic respiration. To the biochemist, metabolic reactions are based on the deployment of enzymes to facilitate energy-yielding chemical reactions between biomolecules. Enzymes are biological catalysts that enable these reactions to occur under relatively isothermal conditions. What type of chemical reactions are important in biochemistry? Redox reactions essentially. We have defined a minimal set of materials that afford a diverse set of functions required to build our photolithoautotroph, in order to minimize the amount of chemical processing required within the self-replication loop.

The only fly in the ointment is the necessity of importing sodium chloride from Earth, as NaCl is scarce on the Moon. On the flip side, this 'salt contingency' does, however, act as a safeguard to shut down the self-replication process through the denial of salt. To reduce our thermal energy requirements, a compromise with electrochemistry allows us to employ a general-purpose method for reducing mineral oxides into pure metals with high purity using a CaCl2 electrolyte. In fact, the Metalysis FFC process is under development on Earth as a means to efficiently reduce rutile into titanium metal.

RepRap 3D printer





Custom in-house Cartesian 3D printer less extruder heads

Most biological macromolecules are constructed from sequences of simpler precursor units. The obvious example is the construction of proteins from amino acids at the ribosomes. The ribosome builds a linear sequence of amino acids according to the nucleotide encoded on the adaptor molecule tRNA. There are two interesting issues here. First, the 1D amino acid sequence is frequently sufficient to direct how the protein configures itself into a 3D macromolecule, the shape of which determines its functionality. Are there alternative means for building 3D structures from smaller units such as 2D layers? I suggest that 3D printing provides an analogue that is capable of implementing the universal construction requirement of the von Neumann self-replicator. The RepRap (replicating rapid prototyper) 3D printer was capable of 3D printing some of its own plastic structural parts either as replacement (self-repair) or for a copy (self-replication).

3D printed electric motor (except wire coils)

We are building our own in-house multi-material 3D printer, initially to print with molten aluminium powder and liquid silicone plastic from solid feedstock. Fortunately, solid silicone plastic tolerates contact with molten aluminium, demonstrating the compatibility of electrical/thermal conductors with electrical/thermal insulation. Once complete, we shall be able to print passive-component circuit boards and structural endoskeletons.

A future version of the 3D printer will extend its capabilities to higher temperatures to work with molten iron alloys and 3D printed ceramic. The ceramic may be printed as silicone plastic for ease of extrusion and then flash heated in oxygen to yield silica ceramic. Molten metal can then be laid on top with further silicone plastic layers added, and the process repeated. In order to demonstrate universal construction, we must 3D print entire robotic machines – this includes actuators, sensors and computing circuitry. We have almost demonstrated a fully 3D printed electric motor, a major step forward in proving the universal construction mechanism of 3D printing.

The inspiration for this process is the wide variety of molecular motors in the biological world. One thing we have learned is that motile capability is essential to all life (even if obtained for free through passive diffusion). We have yet to demonstrate 3D printing of sensors but note that the most basic form of displacement sensing can be implemented as potentiometers (variable resistors) and distance sensing can be achieved through light-sensitive elements such as selenium. With regard to computing, active electronic devices are the fundamental unit. The notion of attempting to replicate complex solid-state foundry techniques to manufacture transistors is implausible. One possible alternative is to take a leaf out of the steampunk manual – vacuum tubes pre-date transistors and require only a handful of the same materials to manufacture. Although we have yet to demonstrate 3D printed vacuum tubes, we have been 3D printing test-pieces using the materials from which a vacuum tube can be constructed. The next problem is to build a computer from vacuum tubes and configure them into neural network circuits rather than a more traditional central processing unit used in conventional computers. Neural networks can do whatever a computer can do. We have already built some of these test circuits to demonstrate their capabilities. Going back to the RepRap 3D printer, which could print most of its plastic structure, we have the prospect of 3D printing the machine's own metal structures, motors, electronics and control programme, starting from its raw constituents. In other words, it would be fully self-replicating. Furthermore, all the ancillary machines such as rovers with scoops, drills and unit chemical processors can be similarly constructed since all robotic machines are kinematic configurations of motors.

Photosynthesis involves the reduction of carbon dioxide into sugars and the oxidation of water into oxygen energized by solar photons. A crucial role in this process is played by chlorophyll, essentially a magnesium atom surrounded by a ring of aromatic units acting as antennae. This energy is transmitted through an electron transport chain and ultimately produces ATP for energy storage through the phosphorylation of ADP. Is it conceivable that we could construct life – let's call it a photolithoautotroph – based on a hearth-based chemistry that replaced enzyme catalysis with thermal means to facilitate metabolism? Could this thermal energy be generated from solar sources? We have been using Fresnel lenses to concentrate solar energy into high temperature beams to thermally process raw materials as outlined earlier.

Thermionic conversion is implemented in vacuum tubes that convert a hot cathode into a stream of electrons. It is this electrical energy that energizes motors and computing circuits. In addition to production, means to store energy will be crucial. The most efficient means to achieve this is to use flywheels – so-called electromechanical batteries, powered by electric motors. Here, we have an example of exaptation where the core components required for actuation (motors) and electronics (vacuum tube) are co-opted for applications in energy supply and storage.

The capacity to pass on information to the next generation of machines will be crucial. Contrasted against the Watson–Crick template pairing necessary for DNA replication, copying of magnetic core memory is relatively trivial. Magnetic induction can be exploited to induce a copy of data stored in one magnetic core array to the blank cells of another. A more interesting proposition concerns the fidelity of the data. In order to ensure controllability of future generations, they cannot be permitted to evolve. The implementation of error detection and correction codes adds redundant checkbits that allow the location of errors (the equivalent of point mutations) to be determined and corrected.

In conclusion, what is life? Three commonly cited properties of life are the existence of metabolism, self-replication with inheritance of characteristics and subjection to evolution. Our machine possesses the first two properties. I am attempting to limit the third property – perhaps, this is hubris and that such a machine would indeed be alive… ■

Further reading

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