Abstract #1661

English

SELF-REPLICATING MACHINES: FROM THEORY TO PRACTICE

We shall review theoretical work on self-replicating machines to determine any practical lessons that might be learned in translating from theory to practice. Theoretical work on self-replicating machines has strongly emphasised self-assembling systems assuming that complex parts are already available in the environment. Indeed, most practical work to date has similarly emphasised robotic assembly of pre-existing complex modules. For true self-replicating machines, this is insufficient and the entire supply chain from mining to extraction must be considered. Nevertheless, there are useful lessons to be learned from self-assembly models, particularly the central role played by robotic machines in the self-replication process. In theoretical models, they are abstracted as assembly manipulators but practical systems must include mining vehicles, physical and chemical processing plants, 3D printers, manufacturing tooling and assembly manipulators. The core components of these kinematic machines are motors and electronic controllers. Construction of such components from raw materials would constitute an existence proof for practical self-replicating machines.

French

No abstract title in French

No French resume

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Biography submitted with the abstract

Prof Ellery is a Canada Research Chair in Space Robotics & Space Technology at Carleton University. He has 170 publications including the authorship of two textbooks in the field of space robotics - An Introduction to Space Robotics (2000) and Planetary Rovers (2016). His interest in robotic in-situ resource utilisation stems from his conviction that the space environment will only open up for viable exploration and commercial exploitation once a robotic infrastructure is emplaced on the Moon, asteroids and Mars constructed from in-situ resources. The only means to achieve this at a reasonable cost will be through self-replicating machines.

Biography in the user profile

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Self-Replicating Machines: from Theory to Practice

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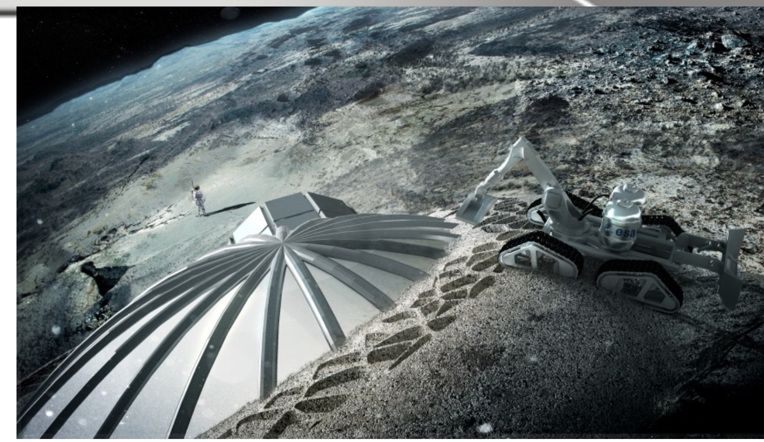
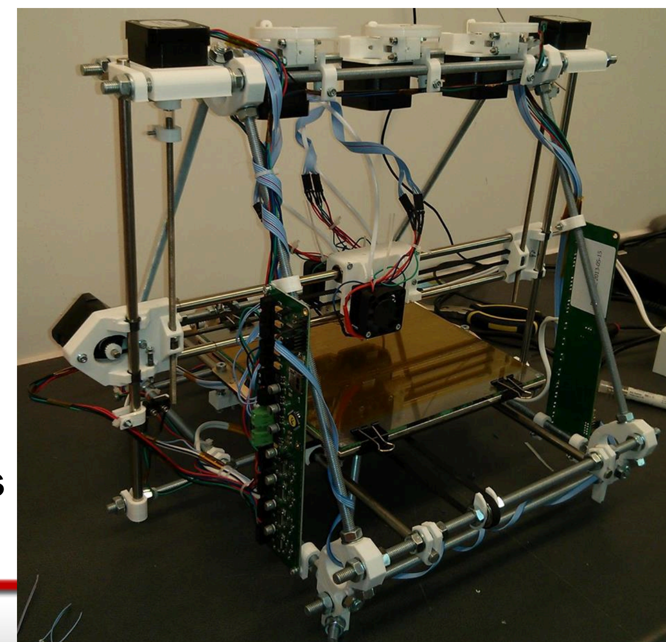
Preamble

- We have previously presented the concept of a self-replicating machine on the Moon
- There are many variations on this theme
- My initial inspiration began with the RepRap FDM 3D printer - it can print some of its own plastic parts
- Full self-replication requires 3D printing:
  (i) structural metal bars and components
  (ii) electric motor drives
  (iii) electronics boards
  (iv) computer hardware/software
- Full self-replication also requires:
  (i) self-assembly
  (ii) self-power
  (iii) material processing into feedstock (wire)
- **From electric motors and electronics, all else follows**





Kinematic Machines

- 3D printers = XY printing head on Z deposition table = cartesian robot
- 3D printable **motor system** including **actuators**, control **electronics** and **sensors**:

  (i) replace 3D printer head with 3 DOF wrist for parts assembly

  (ii) construction of FabLab manufacturing tools – lathe, milling station, drill press, bending press, etc

  (iii) actuators for pumps and stirrers for unit chemical processes

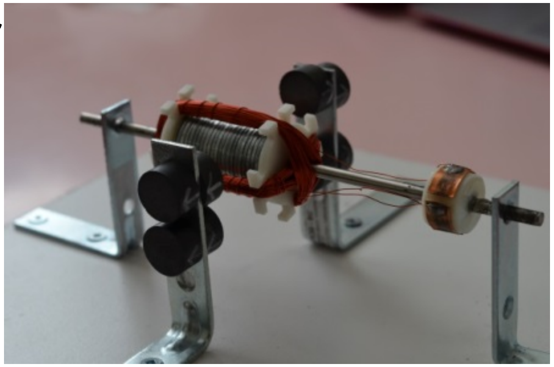
  (iv) beneficiation with crusher jaws

  (v) centrifugal ball milling for surface finishing

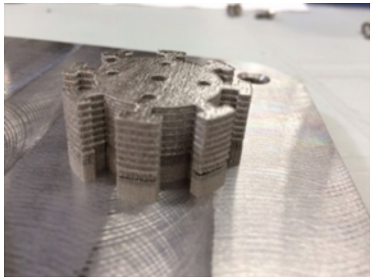
  (vi) vehicle **mobility** for mining with drilling/trenching/excavation mechanisms

  (vii) serial **manipulators** with end-effectors – model of von Neumann's Universal Constructor
- Any kinematic machine is a specific configuration of motors

Electric Motors



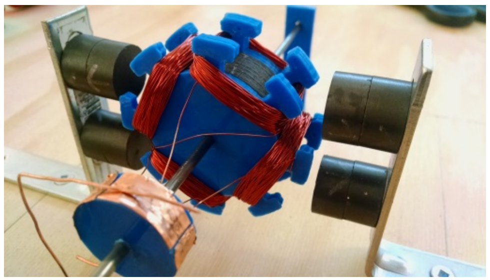
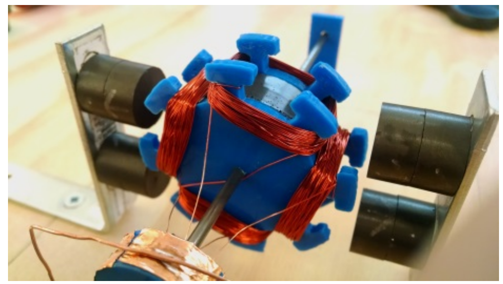
- We focus on the motor core of traditional DC electric motor
  (a) **Plastic-coated wires** are **coiled** around grooved insulating **end-bobbins**
  (b) Motor core constructed from **alternating layers of silicon electrical steel** (up to 3% Si) **and insulating plastic/ceramic** to minimise eddy currents but maximise magnetic threading
- **SLM**-printed motor core by **Renishaw** Canada
- Unfortunately, 316L steel!
- **NRC Canada** - **EBF3** to print Si steel motor core with kovar-based coils



- Submitted ESA bid to fund this activity adequately….
- Advantage – high magnetic threading capability

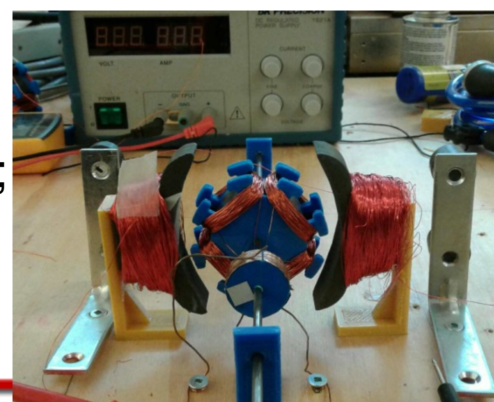
3D Printed Motor Core

- Our motor core comprises Fe powder in a PLA matrix
- 50% Fe filings in PLA matrix by mass (ProtoPasta)

- 50% Fe filings in PLA by volume (NRC Can)
- We are building motors with Si steel powders in PLA to prevent detent

- ProtoPasta-based stator gives insufficient B-field
- Solution (a) ProtoPasta; (b) NRC; (c) DIY

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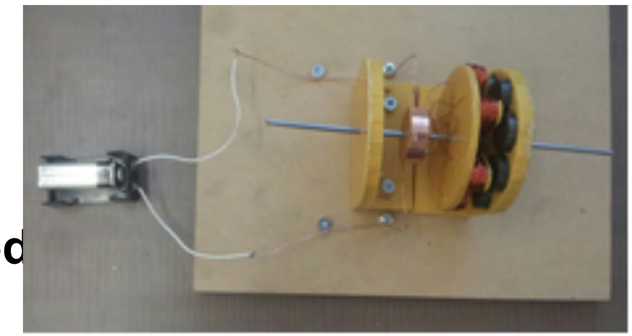
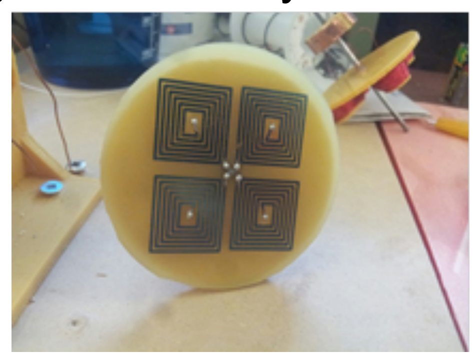
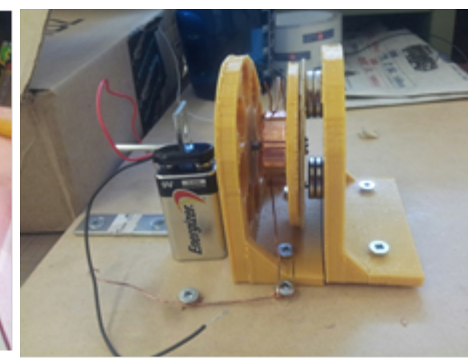
3D Printed Wire Coils

- Pancake motor concept is an alternative motor configuration



- We are exploring **lithographically-printed** wiring patterns
- Single layer insufficient – multilayer design is underway
- Once motor core with wire coils have been printed, a complete 3D printed motor can be constructed

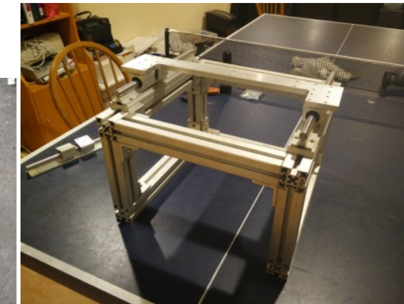


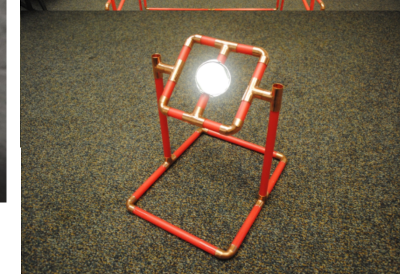


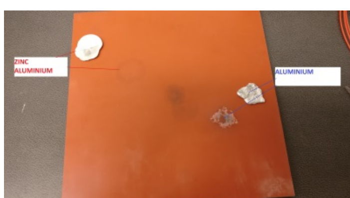
- Dual excitation motor uses core module for both rotor and stator poles
- This still requires manual assembly
- We shall explore design space of 3D printed motor designs using **genetic algorithms**

DIY 3D Metal Printers

- New “hobbyist” 3D printer to print in multiple materials including metals
- An integrated **milling head** will provide surface machining
- There are three power sources:
  (a) **Propane burner** to heat a crucible
  (b) **Induction melter** piped to an extruder printing head
  (c) **Fresnel lens** to focus light onto a fibre optic bundle fed into printing head
- Al wire tracks printed onto silicone plastic insulation for short times







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Demonstrate 3D printing of embedded RC circuits

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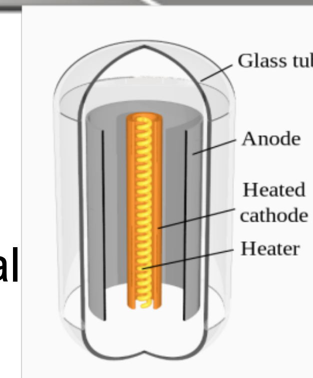
Higher Temperatures

- A lunar solar furnace-based foundry based on printed or cast Fresnel lens concentrators to create temperatures ~2700^{o}C
- Regolith can be directly sintered into superior **glass** at 1300^{o}C
- Anorthite $CaAl_2Si_2O_8$ for fibreglass
- Temperatures of 1600 are sufficient for **steel alloys**
- Print kovar wire onto pre-ceramic silicon plastic substrates
- **Silicone plastic converted to silica ceramic** by high temperature combustion in oxygen

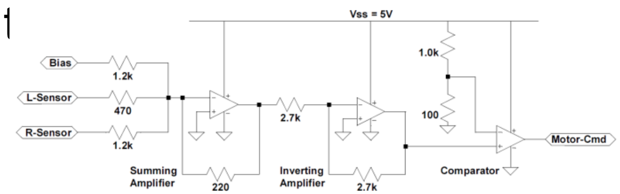
$$SiO_xC_y + (1\text{-}x+2y)O_2 \rightarrow SiO_2 + yCO_2$$

- Silicone plastic 3D printed using FDM – converted to ceramic with CO_2 recovery – steel printed onto silica substrate
- Multi-material 3D printing!

Neural Circuitry

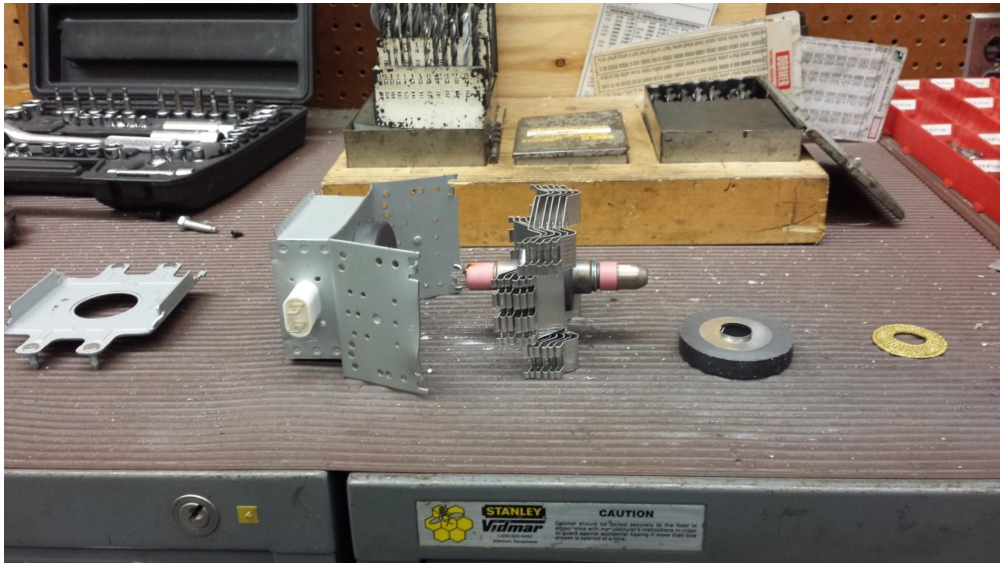


- **Vacuum tubes** are thermionic devices which use sintered **tungsten** resistance wire and **Ni** electrodes to heat cathode to ~1000°C in an evacuated **glass** envelope
- **Problem**: circuit complexity growth using von Neumann computational architecture
- We adopt Turing-complete **recurrent neural nets** composed of analogue neurons
- 3D printer acts as printing head of universal Turing machine printing neural net ccts (output) codified in iron core memory circuits (input
- Our modified **Yamashida-Nakaruma** neuron comprises weighted input, summing integrator and signum output
- Neural nets act as **compressed programs** with log footprint growth with task complexity



Vacuum Tubes

- First vacuum tube to be reverse engineered for 3D printing is magnetron – a macroscopic vacuum tube with “motor” elements



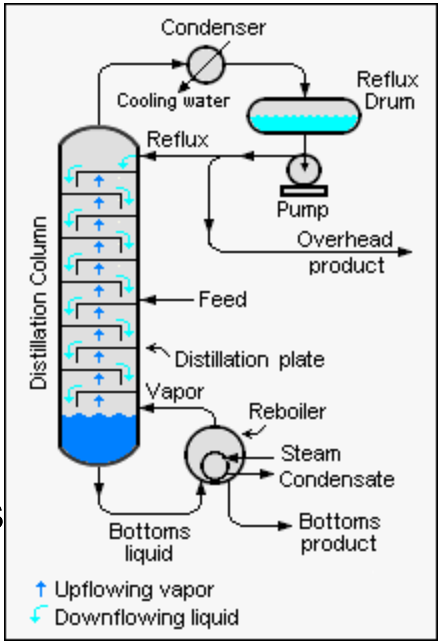
- Curious construction…
- Goal: 3D print solar power microsatellites….

Lunar Plenty

Functionality	Lunar Material
Tensile structures	Wrought iron
Compressive structures	Cast iron
Elastic structures	Steel springs/flexures Silicone elastomers
Thermal conductors	Fernico (eg. kovar)
Thermal insulation	Glass (fibre) Ceramics such as TiO_2
Thermal tolerance	Tungsten
Electrical conduction	Fernico (e.g. kovar) Nickel
Electrical insulation	Glass Ceramic such as TiO_2 Silicone plastic Silicon steel
Active electronics	Kovar Nickel Tungsten Glass
Magnetic materials	Silicon steel Permalloy
Sensors and sensory transduction	Quartz Selenium
Optical structures	Polished nickel Glass
Liquids	Silicone oils Water
Gases	Oxygen Hydrogen

Lunar Volatiles

- RPM will demonstrate extraction of volatile from the lunar regolith, particularly water ice from lunar pole region
- Solar wind has impregnated regolith with 96% hydrogen (~120 ppm), almost 4% He and trace amounts of H_2O, **C**O, **C**O_2, **C**H_4, **N_2**, **N**H_3, H_2**S**, **S**O_2, and noble gases such as **Ar**
- Gases are **preferentially adsorbed** onto small particles of ilmenite
- Mining is simple – scoop regolith into hopper
- Beneficiation may be achieved through **motor**ised rock-jaw crushing and electrostatic/magnetic separation
- Heating regolith to 700°C releases 90% of volatiles
- Fractional distillation may be employed to separate gas fractions
- Reaction chambers require **motor**ised pumps and valves to control flow



Carbon-Modest Silicone

- Plastic is restricted to **flexible electrical insulator** but we need to reduce C inventory imposed by hydrocarbon plastics
- **Silicones** $(R_2SiO)_n$, have O-Si-O backbones - simplest is PDMS silicone oil
- Silicones are radiation-tolerant and temp resistant to 350^{o}C (cf. 120^{o}C)
- **Syngas** is converted to methanol over Al_2O_3 catalyst at 250^{o}C and 5-10 MPa:

  $CO + H_2 \rightarrow CH_3OH$
- Chloromethane by reacting methanol with HCl over Al_2O_3 catalyst at 350^{o}C:

  $CH_3OH + \mathbf{HCl} \rightarrow CH_3Cl + H_2O$
- CH_3Cl is reacted with Si at 370 degrees with Cu (?) catalyst:

  $2CH_3Cl + Si \rightarrow (CH_3)_2SiCl_2$
- This is hydrolysed to PDMS:

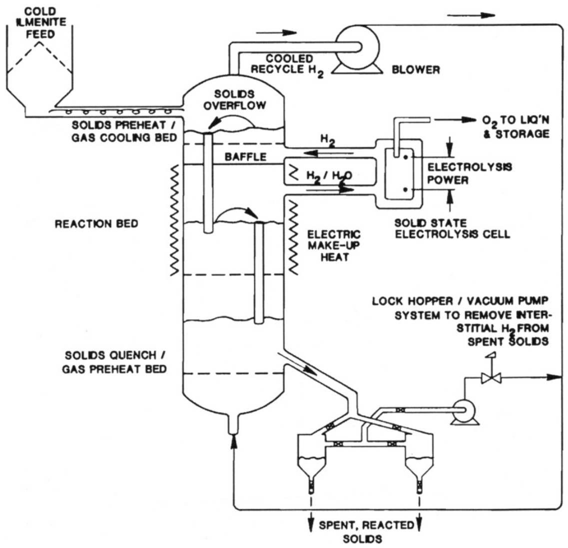
  $n(CH_3)_2SiCl_2 + nH_2O \rightarrow ((CH3)_2SiO)_n + 2nHCl$
- **HCl is recycled - Cl must be imported from Earth**
- Silicone oil may be used for **hot isostatic pressing** of metal powders

Iron Alloys for Motors

- RPM will demonstrate **hydrogen reduction of ilmenite** at ~1000°C to create oxygen, iron and rutile (proposed for RPM)

$FeTiO_3 + H_2 \rightarrow Fe + TiO_2 + H_2O$

$2H_2O \rightarrow 2H_2 + O$



- Hydrogen is recycled
- TiO_2 fibres for thermal insulation
- **Wrought iron** is tough but malleable
- **Tool steel** with <2% C + 9-18% **W** for cutting tools
- **Silicon steel** (up to 3% Si + >97% Fe) for motors
- **Kovar** is high electrical/thermal conductivity Fe alloy

(53.5% Fe, 29% **Ni**, 17% **Co**, 0.3% Mn, 0.2% **Si** and <0.01% **C**) – one of a family of Fernico alloys

- **Permalloy** (80% Ni and 20% Fe) for magnetic shielding with μ_r~10^5

Tunico (W-Ni-Co) Elements

- Mascons in impact craters indicate location of NiFe meteorite ores – detectable as magnetic anomalies, eg. rim of South Pole Aitken crater
- Kamacite/taenite (NiFe alloys) is typically contaminated with Co
- Mond process at 40-80^{o}C reacts impure Ni with CO and S catalyst which is reversed at 230^{o}C/60 bar: $Ni(CO)_4 \leftrightarrow Ni + 4CO$
- S catalyst recovered at 750-1100^{o}C from troilite (FeS) in meteoritic inclusions, lunar regolith (~1%), or lunar volatiles
- Co fraction of NiFe alloy adjusted by mixing recovered Fe and Ni metal
- Highland rock has ~0.3 μg/g W but W is difficult to extract from wolframite ($Fe,Mn(WO_4)$)
- Meteoritic NiFe alloys enriched in W microparticle inclusions which can be crushed and separated by froth flotation (W has high density of 19.3)

Power of Carbothermal Reduction

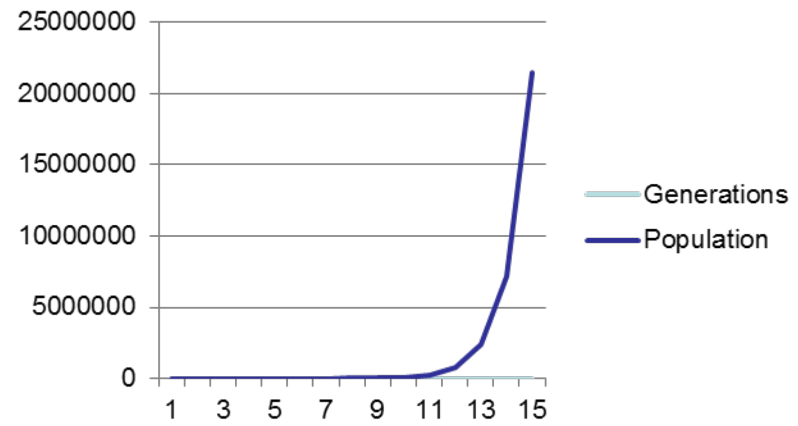
- Carbothermal reduction of lunar anorthite ($CaAl_2Si_2O_8$)
  $4CH_4 \rightarrow 4C + 8H_2$ (T=1400°C)
  $CaAl_2Si_2O_8 + 4C \rightarrow CaO + Al_2O_3 + 2Si + 4CO$ (T=1650°C)
  $Al_2O_3 + 3H_2 \rightarrow 2Al + 3H_2O$ (T=1200-1300°C)
- Carbothermal reduction of lunar olivine (Mg_2SiO_4):
  $Mg_2SiO_4 + 2CH_4 \rightarrow 2CO + 4H_2 + 2MgO + Si$ (T= 2000°C)
- There are other relevant reactions to recycle and recover reagants

Self-Replication is Low-Cost!

- Initial capital cost is amortised over an exponentially increasing productive capacity

$$P = \sum_{i=1}^{m} (1+r)^{i}$$

where r>1



- Specific cost drops exponentially because productive capacity grows faster than discount losses
- For r=2 over 13 generations, specific cost to the Moon has dropped from $200,000/kg to ~$1/kg
- Self-replication is the only means to develop low-cost access to space!