Carleton UNIVERSITY

Self-Replicating Machines are the only means through which to spread through the Solar System

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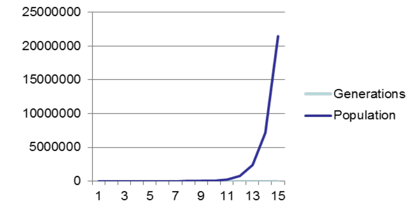
Space Portal Commercial Space Lecture Series, 2 Jun 2021

Power of Self-Replication

- **Self-replication** is the ONLY robust approach to space exploration
- **Self-replication** offers **exponential** growth in productive capacity

  P= $(1+r)^i$ where r>1

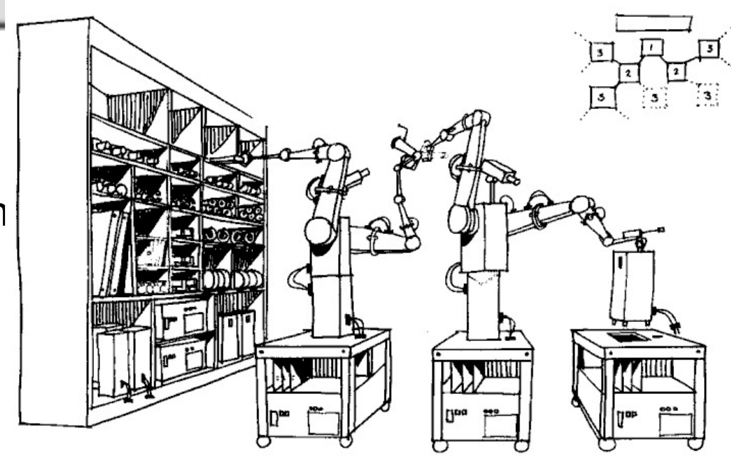


- This is a cellular approach in which each cell factory is identical
- Consider launch of a single 10 tonne self-replicating factory to the Moon at a cost of $7.5 B

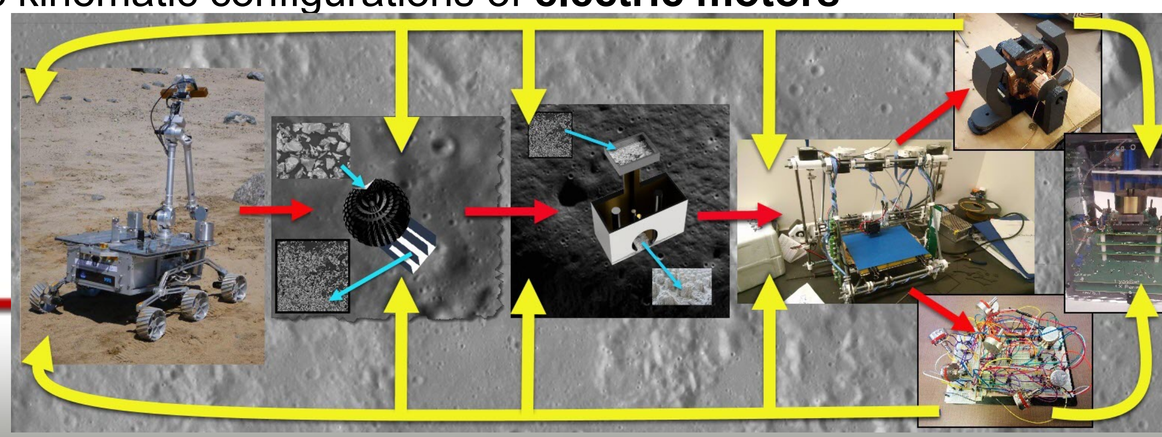
Number of offspring per generation	Number of generations	Population	Specific Cost ($/kg)
1	10	1024	
2	7	2187	<$1000/kg
2	13	1,594,323	<$1.25/kg

- Cumulative population is >**1.5×10^6 within 13 generations**
- Initial capital cost of $7.5 B is amortised over an exponentially increasing productive capacity
- For r=2 over 13 generations, specific cost to the Moon has dropped from $750,000/kg to **<50 cent/kg** of productive capacity
- If each 10 tonne factory takes 6 months to build, we have >1.5 million factories in 6.5 years
- If each of the10^6 factories produces 10^3 solar power satellites, we have10^9 SPS units
- We could supply our global energy needs cleanly from space
- **SELF-REPLICATION EFFECTIVELY SIDESTEPS LAUNCH COSTS**

Universal Constructor ⊃ Self Replicator



- John von Neumann – a sufficient (but not necessary) condition for self-replication is universal construction
- **Universal constructor is a kinematic machine** that can manufacture any other machine *including a copy of itself*
- UC is generalisation of the universal Turing machine
- UC is idealised as a programmable “generalised” kinematic arm in a sea of parts (structured environment)
- We adapt UC to unstructured environments through a suite of **kinematic machines**: (i) load-haul-dumpers and drills as mining robots; (ii) programmable pumps for driving unit chemical processors; (iii) mills, lathes and 3D printers for autonomous manufacture; (iv) manipulators for robotic assembly
- **Kinematic machines** are specific kinematic configurations of **electric motors**
- **Sensorimotor control** system:
  - motors
  - computational electronics
  - sensors



Minimal Demandite

Moon has a simple geology: pyroxene – plagioclase (anorthite) – olivine - ilmenite

10 basic materials required to supply all full functionality to robotic spacecraft (satisficibility)

We require a minimal set of **reagents** resources including **NaCl imported from Earth – salt contingency**

Functionality	Lunar Material
Tensile structures	Wrought iron – Aluminium
Compressive structures	Cast iron – Aluminium
Elastic structures	Steel/Al springs/flexures Silicone elastomers
Thermal conductor straps	Iron/Nickel/Cobalt/Aluminium Tungsten
Thermal insulation	Glass (silica fibre) Ceramics such as SiO_2 and Al_2O_3
High thermal tolerance	Tungsten, Al_2O_3
Thermal sources	Fresnel lenses/mirrors (optical structures) Electrical heating (iron/nickel/tungsten)
Electrical conduction	Fernico (e.g. kovar) Nickel – Aluminium
Electrical insulation	Glass (fused silica) Ceramics - SiO_2, TiO_2, Al_2O_3 Silicone plastic Silicon steel for motors
Active electronics (vacuum tubes)	Kovar Nickel Tungsten Fused silica glass/ceramic
Magnetic materials	Co-ferrite - AlNiCo Silicon steel Permalloy
Sensors and sensory transduction	Resistance wire Quartz Selenium
Optical structures	Polished nickel/aluminium (mirrors) Fused silica glass (lenses/fibres, etc)
Lubricants	Silicone oils Water
Adhesives	Silicone elastomer/gels
Fuels	Oxygen – Hydrogen Electromagnetic launchers + solar sails

Self-Replication requires Closure

- UC must be supplied with the appropriate resources to self-replicate: matter+energy+information
- The most important constraints are closure conditions:

(a) Material and parts closure – each component has a portfolio of materials, processes and machines required for its manufacture – to close the matter loop by:

(i) Restricting raw material inventory to minimise mining and chemical processing cost, e.g. demandite list, industrial ecology, Metalysis FFC process

(ii) Restricting parts inventory to minimise manufacturing and assembly cost, e.g. 3D printing

(b) Energy closure – energy generation must exceed energy cost (energy return on investment (EROI) – to close the energy loop by:

(i) Maximise use of direct environmental energy, e.g. thermal energy for chemical processing

(ii) Maximising electrical energy conversion efficiency, e.g. PETE >30%

(iii) Minimise energy wasted in processing waste by eliminating waste, e.g. industrial ecology

(iv) Restrict all physical processes to minimise energy consumption, e.g. Metalysis FFC process, 3D printing

- **(c) Information closure** – information required for specification does not exceed capacity to store/process specification - to close the information loop by:

(i) Maximise parts re-use (exaptation) to minimise information specification, e.g. electric motors co-opted for energy storage as flywheels and vacuum tubes co-opted for energy conversion

Lunar Mining

- Processing of mineral in-situ resources requires mining vehicles
- Kapvik is a 32 kg microrover prototype for lunar mining

  (i) JCB prototype with regolith scoop

  (ii) autonomous navigation capability using UKF implemented on two FPGAs

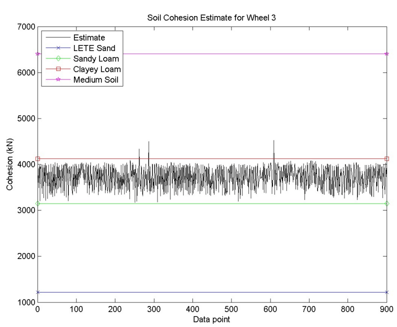
  (iii) reconfigurable chassis, e.g. elastic loop mobility system for high traction on rugged terrain

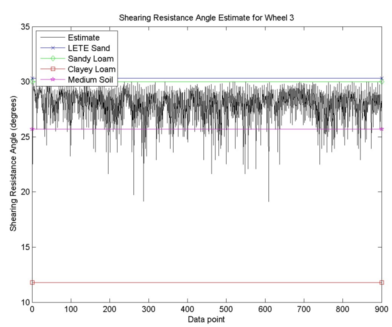
  (iv) sensorised chassis for online regolith characterisation

  (v) hybrid 4 DOF camera mast/manipulator arm

  (vi) pan/tilt camera at elbow with full observability of scoop

  (vii) abseiling capability for crater surveying



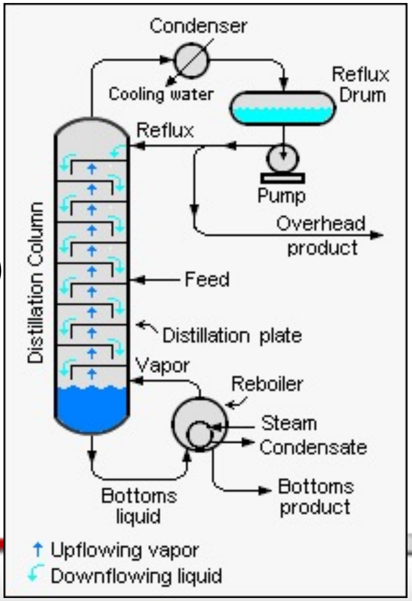


Lunar Volatiles

Volatile species	Concentration (ppm/µg/g)	Mass/m³ regolith (g) assuming 1660 kg/m³ density
H	46±16	76
^3He	0.0042±0.0034	0.007
^4He	14±11	23
C	124±45	206
N	81±37	135
F	70±47	116
Cl	30±20	50

- Volatiles mining by heating regolith to 700°C releases 90% of volatiles esp from smaller ilmenite particles (extracted magnetically): 96% H_2, <4% He, **C**O, **C**O_2, **C**H_4, **N**$_2$, **N**H_3, H_2**S**, **S**O_2, Ar, etc
- **Carbon compounds** ~80-120 ppm

- **Fractional distillation** for well-separated fractions (assuming STP):
  He (4.2 K), H_2 (20 K), **N_2 (77 K)**, **CO** (81 K), **CH_4** (109 K), **N_2O** (185 K), **CO_2** (194 K), **H_2S** (213 K), **NH_3** (240 K), **SO_2** (263 K) **NO_2** (294 K) and H_2O (373 K)
- **VERY VALUABLE STUFF!!!!**
- We should husband this stuff as we extract water ice……



Plastics/Ceramics Manufacture

- Ceramics – **fused silica glass** – may be adopted for electrical insulation of cables
- Ceramics – **porcelain from fired kaolinite** – may be adopted for electrical insulation of junctions
- Knob-and-tube technology for electrical distribution
- We adopt **silicone plastics** with multiple advantages over hydrocarbons

  (i) Si backbone **minimises C resource consumption**

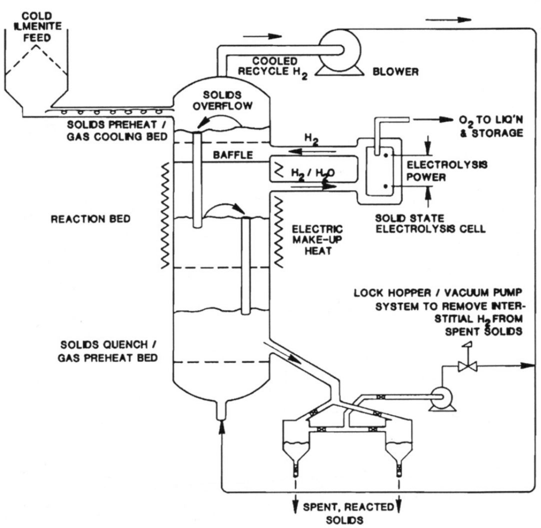
  (ii) UV radiation resistant

  (iii) High operational temperature tolerance (350^{o}C c.f. 120^{o}C)

  (iv) it is used only sparingly for flexible **wire sheathing**
- From syngas to polydimethylsiloxane **(PDMS) – simplest siloxane** (Rochow process)
- HCl reagent is recycled – **Cl** required from "**salt" contingency** against uncontrolled replication
- **Primary use is for silicone oils**

Iron Age Technology

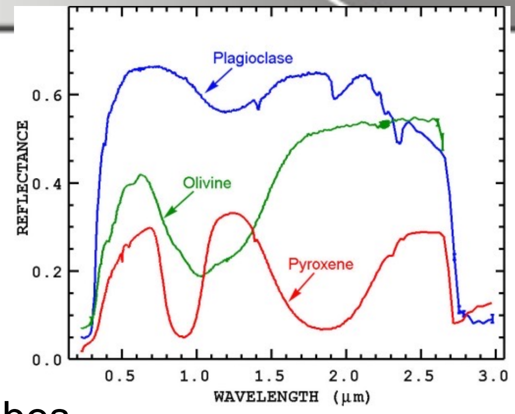
- **Hydrogen reduction of ilmenite** at ~1000°C creates oxygen, iron and rutile
  $FeTiO_3 + H_2 \rightarrow Fe + TiO_2 + H_2O$ and $2H_2O \rightarrow 2H_2 + O_2$
- Fe separated from TiO_2 by liquation at 1600°C
- **Wrought iron** is tough & malleable for tensile structures
- **Cast iron** (~2-4% **C** + 1-2% **Si**) is more brittle for compressive structures (e.g. Iron Bridge for 200+y)
- **Tool steel** (<2% **C** + 9-18% **W**) for cutting tools (eg. milling head
- **Silicon (electrical) steel/ferrite** (up to 3% **Si** and 97% Fe) for electromagnets and motor cores
- **Kovar** (53.5% Fe, 29% **Ni**, 17% **Co**, 0.3% Mn, 0.2% **Si** and <0.01% **C**) – fernico alloy with high temperature electrical/thermal conductors
- **Permalloy** (20% Fe + 80% **Ni**) provides magnetic shielding with μ_r~10^5 H/m (replace 5% Ni with Mo gives supermalloy with μ_r~10^6 H/m)



Tunicose Ores from Meteoritic Sources

- We need to source Tungsten, Nickel and Cobalt for our alloy range
- Some 25% lunar impactor material survives impact at or near surface of crater (670 crater >10 km diameter)
- **Mascons** indicate location of **NiFe** meteorite ores, eg. northern rim of SPA crater
- NiFe meteorites dominated by kamacite/taenite (**NiFe alloys**) - typically **contaminated with Co**
- **Mond (carbonyl) process** at 40-80^{o}C reacts impure **Ni** with **CO** and **S** catalyst which is reversed at 230^{o}C/60 bar: $Ni(CO)_4 \leftrightarrow Ni + 4CO$
- Similar carbonyl processes for Co and Fe
- **S** catalyst recovered at 750-1100^{o}C from troilite (**FeS**) in <u>meteoritic inclusions</u>, lunar regolith (~1%), or lunar volatiles (SO_2 and H_2S gases)
- **AlNiCo** permanent magnets
- Meteoritic NiFe alloys **enriched in W microparticle inclusions** which can be crushed and separated (W has high density of 19.3 and high melting temperature of 3422^{o}C)

Preprocessing the Natural Way



- **Carbothermic reduction of anorthite** ($CaAl_2Si_2O_8$) at 1650°C yields $\mathbf{Al_2O_3}$:

  $4CH_4 \rightarrow 4C + 8H_2$ (T=1400°C)

  $CaAl_2Si_2O_8 + 4C \rightarrow CaO + Al_2O_3 + 2Si + 4CO$ (T=1650°C)

  Alumina is refractory material (used in crucible linings) with physical properties exceeded only by diamond

  Quicklime is used as coatings for tungsten cathodes in vacuum tubes
- **Artificial weathering of anorthite** ($CaAl_2Si_2O_8$) with hot **HCl** yields $\mathbf{SiO_2}$ (artificial weathering)

  $CaAl_2Si_2O_8 + 8HCl + 2H_2O \rightarrow CaCl_2 + 2AlCl_3.6H_2O + 2SiO_2$

  $2AlCl_3.6H_2O \rightarrow Al_2O_3 + 6HCl + 9H_2O$

  Silica is raw material for **fused silica glass** (eg. Fresnel lenses) and **quartz** manufacture

  $\mathbf{CaCl_2}$ **electrolyte** for FFC process as a byproduct
- **Quartz (piezoelectric)** does not occur naturally on the Moon but it may be **grown from silica**

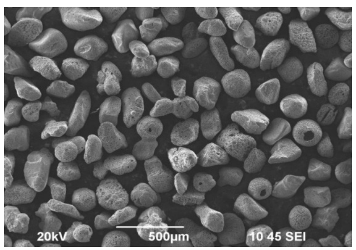
  Melt silica at 2000°C followed by seeding in Na_2SiO_3 ($\mathbf{Na}_2CO_3+SiO_2 \rightarrow Na_2SiO_3+CO_2$ at 1700°C) at 350°C and 150 bar
- **Alumina and silica may be reduced to aluminium and silicon metals directly**

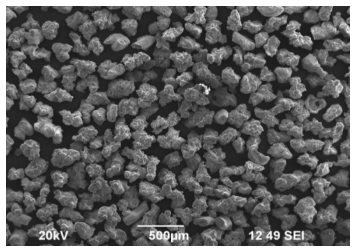
Electrolytic Metalysis FFC Process = Universal Chemical Processor

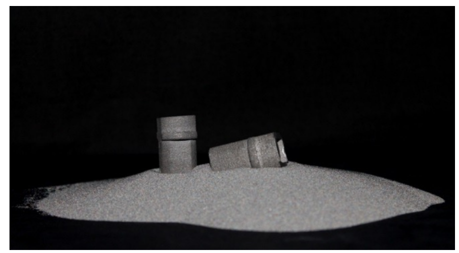
- Cathode is sintered solid metal oxide (applicable to all metal oxides) – **solid state** reaction

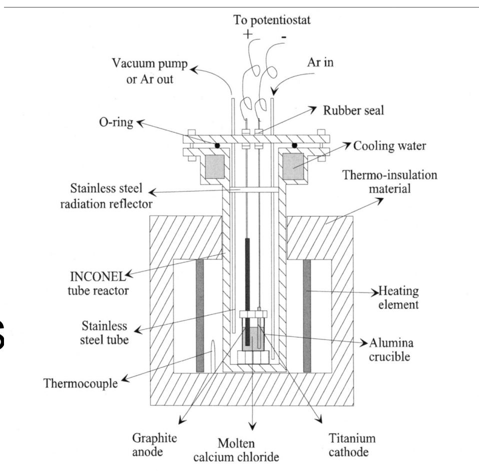
  $MO_x + xCa \rightarrow M + xCaO \rightarrow M + xCa + ½xO_2$

  $CaO + 2NH_4Cl \rightarrow CaCl_2 + 2NH_3 + H_2O$
- **$CaCl_2$ electrolyte** at 900-1100°C with O_2 evolved at the anode (assumed non-eroding) - graphite anode yields **CO/CO_2 – recyclable through Sabatier process**)
- Product is >**99% metal alloy sponge** that can be powdered for 3D printing









TiO_2 powder → Ti powder → 3D printed Ti parts

- Output powder has been directly 3D printed into Ti test parts with SLS
- Metalysis FFC process requires 97% thermal heating and 3% electrolytic energy

Lunar Industrial Ecology

Lunar Ilmenite

$Fe^0 + H_2O \rightarrow$ ferrofluidic sealing

$FeTiO_3 + H_2 \rightarrow \mathbf{TiO_2} + H_2O + \mathbf{Fe}$

$2H_2O \rightarrow 2H_2 + O_2$

$2Fe + 1.5O_2 \rightarrow Fe_2O_3/Fe_2O_3.CoO$ - ferrite magnets

Nickel-iron meteorites

$Fe(CO)_5 \leftrightarrow 5CO + Fe$ (175°C/100 bar) $\rightarrow$

$Ni(CO)_4 \leftrightarrow 4CO + Ni$ (55°C/1 bar) $\rightarrow$

$Co_2(CO)_8 \leftrightarrow 8CO + 2Co$ (150°C/35 bar) $\rightarrow$

Alloy	Ni	Co	Si	C	W
Tool steel				2%	9-18%
Electrical steel			3%		
Permalloy	80%				
Kovar	29%	17%	0.2%	0.01%	

S catalyst

$4FeS + 7O_2 \rightarrow \mathbf{2Fe_2O_3} + 4SO_2$

(Troilite) $SO_2 + H_2S \rightarrow 3S + H_2O$

$FeSe + Na_2CO_3 + 1.5O_2 \rightarrow \mathbf{FeO} + Na_2SeO_3 + CO_2$

KNO_3 catalyst $Na_2SeO_3 + H_2SO_4 \rightarrow Na_2O + H_2SO_4 + Se \rightarrow$ photosensitive Se

W inclusions – high density of 19.3 $\rightarrow$ cathodic material

Olivine

$Mg_2SiO_4 + 2CH_4 \rightarrow 2CO + H_2 + \mathbf{2MgO} + Si$ at 2000°C $\rightarrow$ 3D Shaping binder

$MgO + HCl \rightarrow MgCl_2 + H_2O$ $\rightarrow$ 3D Shaping binder

$CO + 0.5\ O_2 \rightarrow CO_2$

$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ at 300°C (Sabatier reaction) $\rightarrow CH_4 \rightarrow C + 2H_2$ at 1400°C for steel

Ni catalyst

Lunar Anorthite

$CaAl_2SiO_8 + 4C \rightarrow CO + \mathbf{CaO} + \mathbf{Al_2O_3} + 2Si$ at 1650°C $\rightarrow$ CaO cathode coatings

$CaO + H_2O \rightarrow Ca(OH)_2$

$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$

$CaAl_2SiO_8 + 5HCl + H_2O \rightarrow CaCl_2 + 2AlCl_3.6H_2O + \mathbf{SiO_2}$ $\rightarrow$ fused silica glass + metalysis electrolyte

$AlCl_3.6H_2O \rightarrow Al(OH)_3 + 3HCl + H_2O$ at 100°C

$Al(OH)_3 \rightarrow \mathbf{Al_2O_3} + 3H_2O$ at 400°C $\rightarrow 2Al + Fe_2O_3 \rightarrow 2Fe + Al_2O_3$ (thermite)

AlNiCo hard magnets

Al solar sail

Lunar Volatiles

850°C 250°C

$CH_4 + H_2 \rightarrow CO + 3H_2 \rightarrow CH_3OH$ 350°C

Ni catalyst Al_2O_3 $CH_3OH + HCl \rightarrow CH_3Cl + H_2O$ 370°C $+nH_2O$

Al_2O_3 $CH_3Cl + Si \rightarrow (CH_3)_2SiCl_2 \rightarrow ((CH_3)_2SiO)_n + 2nHCl$ $\rightarrow$ silicone plastics/oils

$3NO + H_2O \rightarrow 2HNO_3 + NO$

$2SO_2 + O_2 \leftrightarrow 2SO_3$ (low temp)

$SO_3 + H_2O \rightarrow H_2SO_4$

Salt of the Earth

$NaCl + CaCO_3 \rightarrow Na_2CO_3 + CaCl_2$ $\rightarrow$ metalysis electrolyte

350°C/150 bar

$Na_2CO_3 + SiO_2(i) \leftrightarrow Na_2SiO_3 + CO_2 \rightarrow$ piezoelectric quartz

$NaCl + HNO_3 \rightarrow HCl + NaNO_3$

Lunar Orthoclase

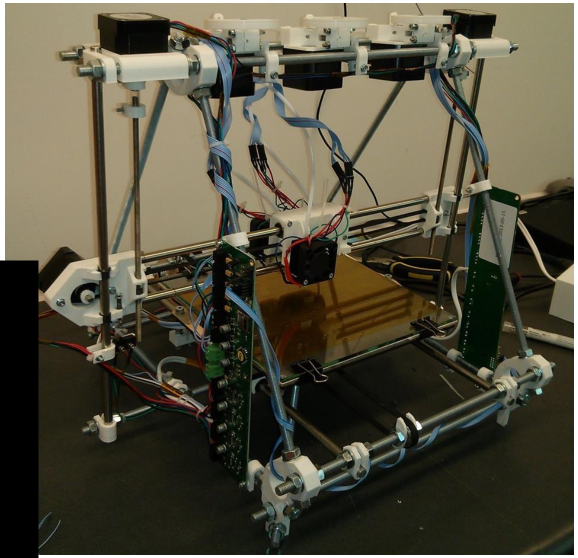
$2KAlSi_3O_8 + HCl + 9H_2O \rightarrow H_4Al_2Si_2O_9 + 2KCl + SiO_2 + H_2O$

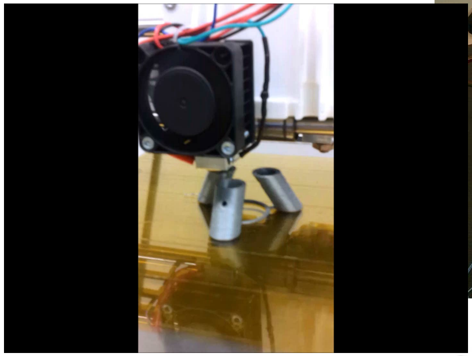
Kaolinite $KCl + NaNO_3 \rightarrow NaCl + KNO_3$

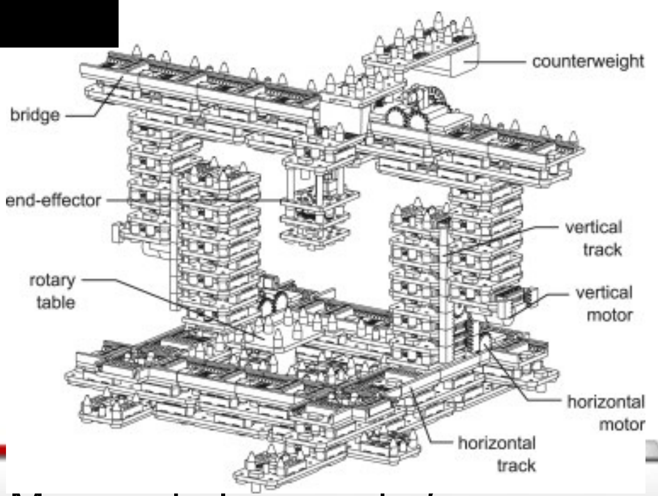
3D Printing = Universal Construction Mechanism

- **RepRap** FDM 3D printer can print many of its own **plastic parts**
- Full self-replication requires 3D printing:
  (i) structural metal bars and components (SLS/M or EBAM)
  (ii) joinery (replaced with cement/adhesive)
  (iii) **electric motor drives**
  (iv) **electronics** boards
  (v) **computer hardware/software**
- Full self-replication also requires:
  (i) self-assembly (proxy for manipulator motors)
  (ii) self-power (solar-thermionic/flywheel)
  (iii) material processing into feedstock - ISRU

From 3D printed electric motors and electronics, *omnia sequitur*…



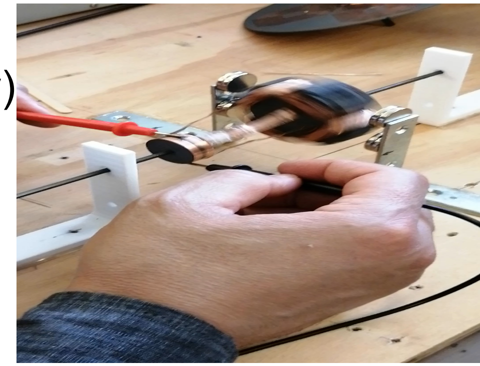


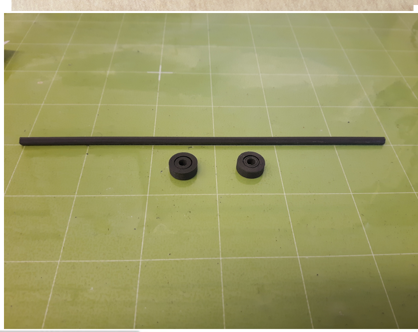


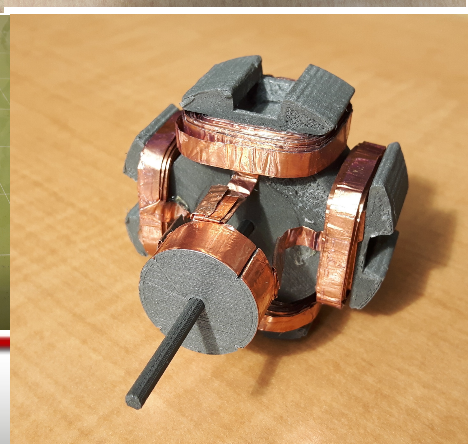
Moses et al concept of universal constructor

Fully 3D Printed Motor

- 3D printed rotor (ProtoPasta)
- 3D printed permanent stator magnet (Oak Ridge National Laboratory)
- LOM-style copper tape wiring/commutator wound around rotor
- 3D printed shaft + bearings







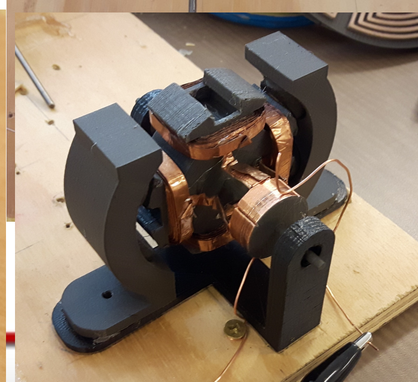


Photo-Sensitive Materials

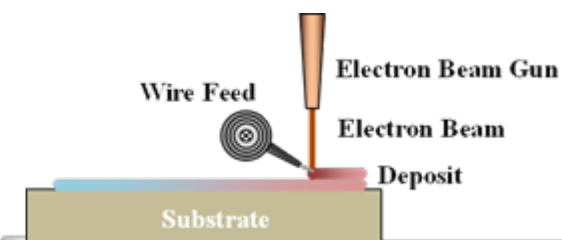
- Imaging camera array is fundamental as a remote distance sensor
- P-type semiconductor **selenium** was used in Victorian photophone
- **Se is found in association with metal sulphides** but, although rare on the Moon, chalcopyrite (Cu-Fe-S) deposits exist
- **S/Se ratio** in carbonaceous meteorites is **~2450** with **S~5%** content of same
- In **NiFe** meteorites, **Se is associated with troilite (FeS) and chalcopyrite (Cu-Fe-S) deposits**
- Iron selenide may be smelted with soda $\mathbf{Na_2}CO_3$ and saltpetre $\mathbf{KNO_3}$:

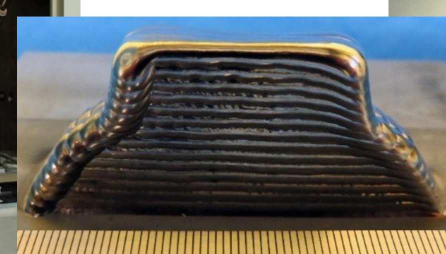
  $FeSe + Na_2CO_3 + 1.5O_2 \rightarrow FeO + Na_2SeO_3 + CO_2$
- Selenite Na_2SeO_3 is acidified with H_2SO_4 that precipitates tellurite impurities out of solution leaving selenous acid (H_2SeO_3) from which **Se may be liberated**:

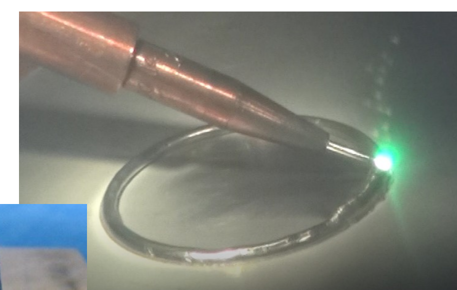
  $H_2SeO_3 + 2SO_2 + H_2O \rightarrow Se + 2H_2SO_4$
- Se is recovered with sulphuric acid recycled
- **Imported reagent Na** is necessary for Se extraction as part of the \`salt\` contingency (Na_2O product is recycled by water into $NaOH + HCl \rightarrow NaCl + H_2O$)
- Photomultiplier is a vacuum tube with electrodes coated with Se (primary emitter) and Al_2O_3/MgO (secondary emitters)

Generalised 3D Printing Suite

- 3D printing offers versatility in manufacturing 3D structures
  All 3D printers = XY printing head on Z deposition table = **cartesian robots**
- We are interested in two technologies – **selective solar sintering** and **EBAM**
- Selective solar sintering uses solar concentrators for generating thermal energy
- We have a 2m x 2m diameter Fresnel lens capable of generating up to ~1500^{o}C spot temperature
- Quartz rod → fibre-optic cabling → **selective solar sinterer**
- **EBAM** is **electron gun** (high voltage **vacuum tube**) but restricted to metals
- Wire-fed EBAM (NRC) can print Ti alloy striucture and Al alloy wiring

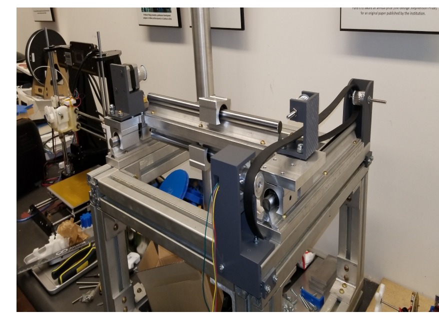




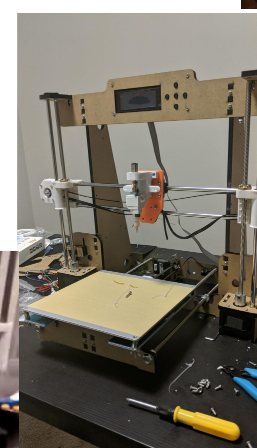


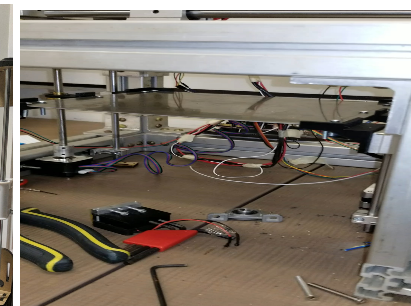
Multi-Material 3D Printer

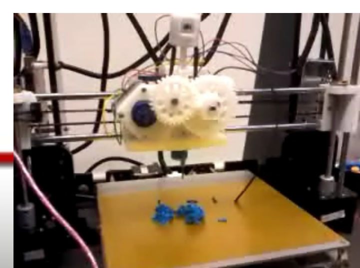
- We are building rigid multi-material 3D printer to print in metals and plastics
- Solar furnace based on 1.2 m x 0.9 m **Fresnel lens** for melting Al alloy in ceramic crucible → 3D printing by **Fresnel lenses**
- We have deposited molten Al wire tracks onto silicone plastic insulation: **Al alloy (440°C m. p.) ↔ silicone (350°C op temp)**
- We have demonstrated metal deposition on plastic!



- Two heads being added – fibre optic and silicone plastic extrusion head
- Phase 2 - 3rd milling head for integrated surface finishing
- Phase 3 – 4th wrist assembly head for component assembly
- Phase 4 – Migrate to steels/silicone-derived ceramics $SiO_xC_y + (1-x+2y)O_2 \rightarrow SiO_2 + yCO_2$
- Initially, we shall **3D print passive electronic circuitry**





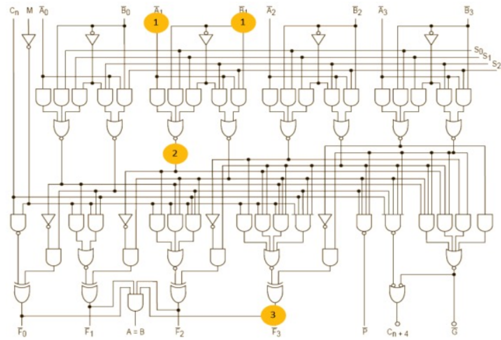


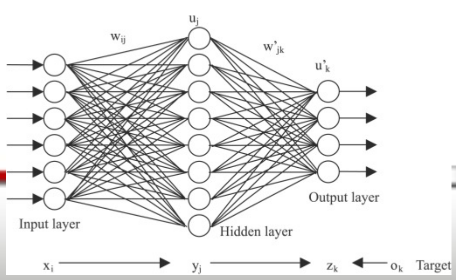
Steam-Punk Electronics

- Vacuum tubes are still used for TWTAs on spacecraft (more rad-tolerant than solid state)
- **Vacuum tubes** are of simple construction that are potentially printable (TBD)
- **Thermionic** devices which use **kovar** resistance wire to heat a sintered **tungsten** cathode coated with **CaO** to 1000-2000^{o}C which evaporates electrons to **Ni** anode and control grid in a evacuated **glass** envelope
- Example: Colossus at Bletchley Park (1943) of 2400 vacuum tubes designed by the great and unsung **Tommy Flowers**
- Problem: circuit complexity growth with task program, e.g. ENIAC with 17,000 vacuum tubes occupied a large room
- **CPU-based architectures grow exponentially**, e.g. 8086 CPU architecture is an early simple von Neumann architecture
- **Modern CPUs are highly complex** – cannot be implemented using vacuum tubes
- Solution:

  (i) General purpose computer architecture can be replaced with **distributed architecture** of specialised circuits

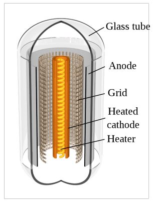
  (ii) Artificial neural nets grow **logarithmically** with task size (Parberry)

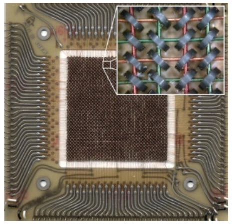




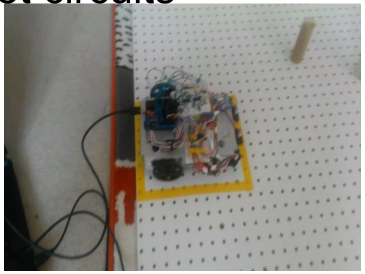
Analogue Neural Nets = Turing Complete

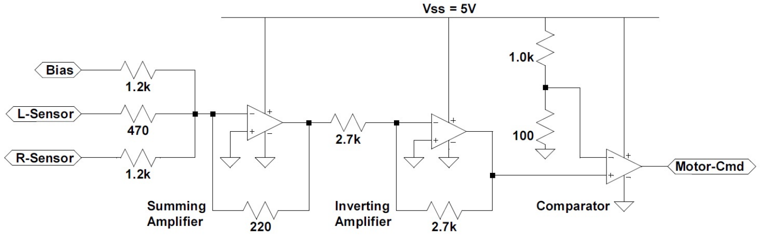
- **Recurrent neural nets are Turing-equivalent** (indeed, analogue neural nets offer super-Turing capabilities)



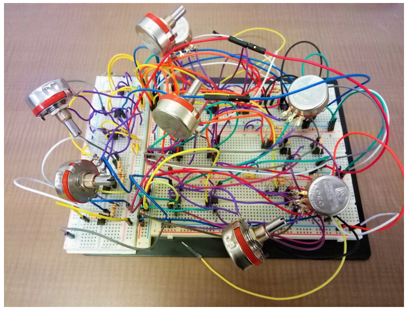


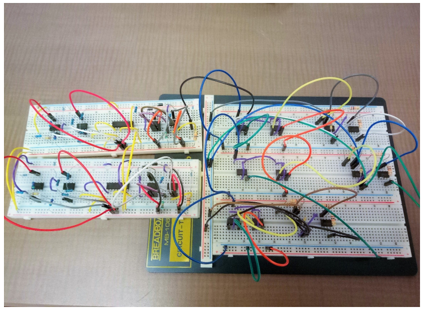
- Direct model of original Turing machine:
  Input tape = magnetic core memory (same components as motor)
  Output tape = analogue neural net circuits
  Read/write head = 3D printer

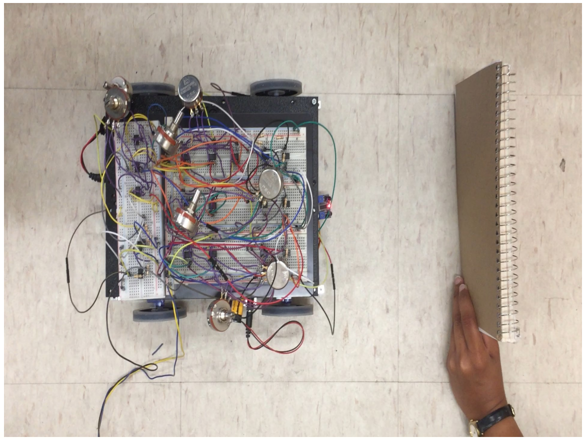




- Modified **Yamashida-Nakaruma** hardware "printable" neuron with fixed weights
- MLP neural net circuit with BP circuit for obstacle avoidance:







- Weights can be updated but not topology – limits on learning
- Implementation of RatSLAM in neural network based on the Rat hippocampus?

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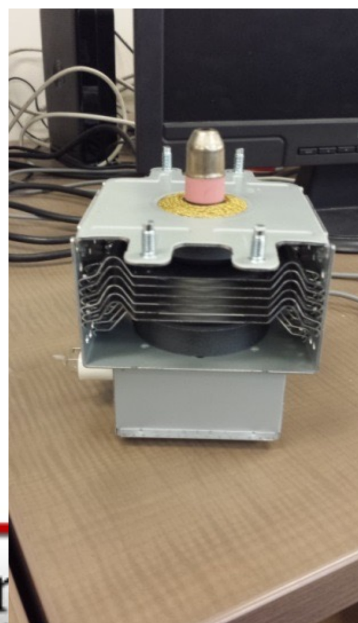
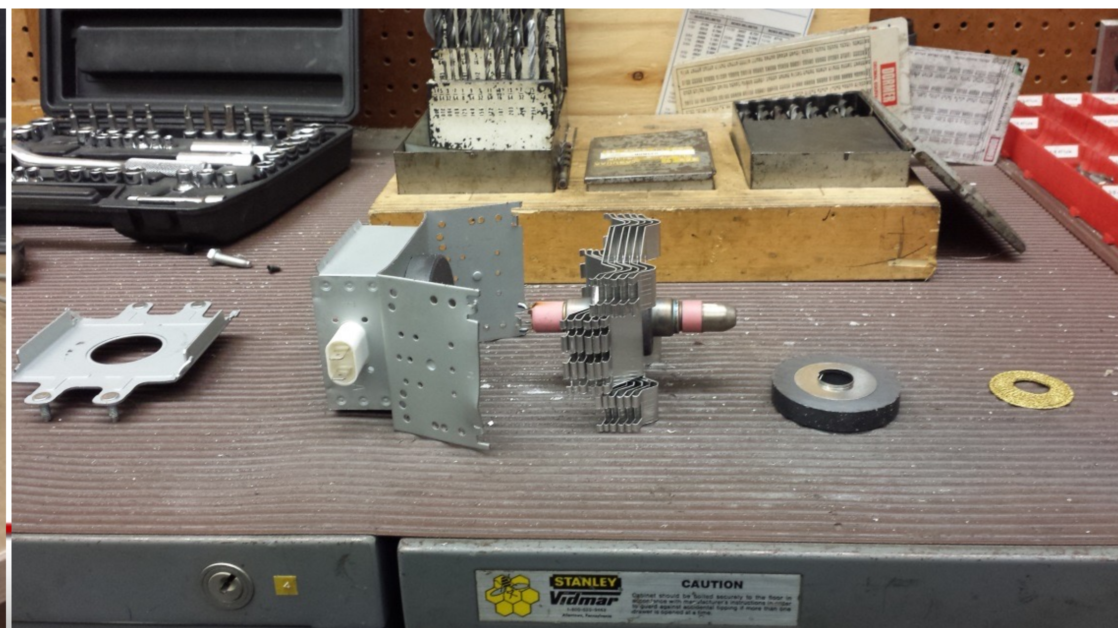
Magnetron

- We intend to 3D print a magnetron – it is a macroscopic vacuum tube with "motor" elements + cooling fins
- We wish to explore direct thermal heating of the cathode using solar concentrators to eliminate electrical conversion stage
- Magnetron is the centrepiece of the SPS
- Magnetron introduces further capabilities for self-replication:

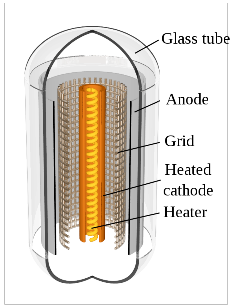
(i) regolith processing; (ii) pn junction doping; (iii) scientific analysis instruments (MIBS)





Electric Power Conversion

- Thermionic conversion in vacuum tube with simple construction
- Work function = min energy required to liberate electrons φ~2-6 eV (dependent on material)
- For most materials, φ>3 eV so T >1000°C required, e.g. 4.52 eV for refractory **tungsten** requires T>1400°C
- Alkaline earth oxide mixture BaO-CaO-Al_2O_3 in 4:1:1 ratio yields φ=2.87 – **only CaO and Al_2O_3 available in-situ from anorthite**
- Al-doped haematite photocathodic coating?
- **To reduce space charge effect**:
  (i) K vapour at > 760°C (similar low ionization potential as Cs)
  (ii) minimize inter-electrode distance ~1-10 μm
  (iii) **electrostatic field by control grid electrode to shape electron transmission – η~40%**



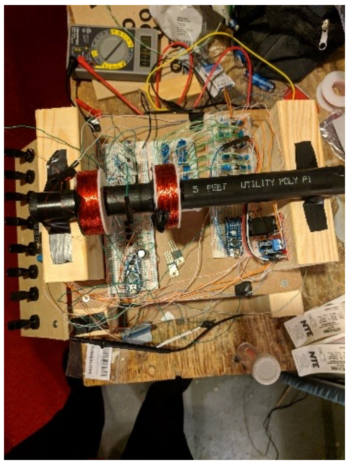
- **Photon-enhanced thermionic emission (PETE) with η=30-50%**
- **Undoped Si has ΔE=1.1 eV offers good response**
- PETE may be supplemented by second stage thermoelectric conversion at anode
- **Thermoelectric Mg_2Si** manufactured by heating SiO_2 with Mg powder (from olivine)
- Conservative estimate **η=30%** (subject to detailed analysis/experiment)

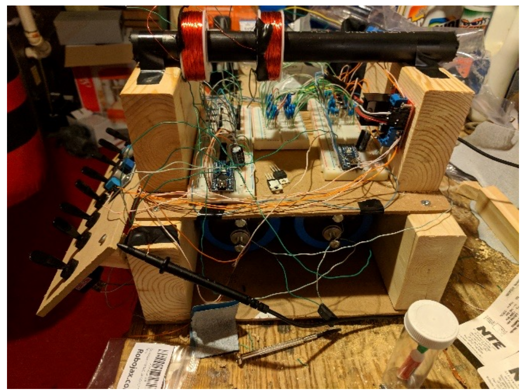
Flywheel Energy Storage

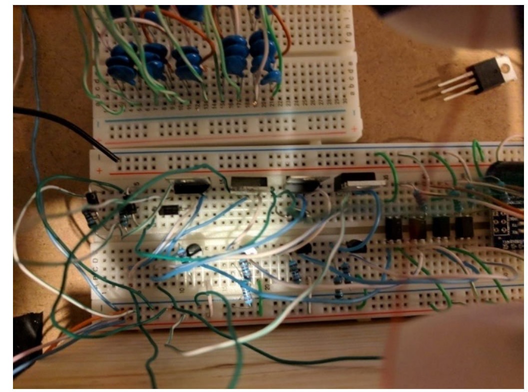
- Electromechanical batteries **(flywheels) offer zero DoD** and insensitivity to charge/discharge cycling
- High energy density ~100 kJ/kg and good power density ~50 Wh/kg
- Energy stored, $E = \frac{1}{4}mr^2w^2 = \frac{1}{2}Iw^2$ where w~20,000-50,000 rpm
- Tangential velocity is determined by wheel material $v = \sqrt{\frac{\sigma}{\rho}}$
- **Specific energy ~30 Wh/kg for steel – 40 Wh/kg for titanium – 100 Wh/kg for glass**
- To minimize radial stresses, rim constructed from concentric hoops separated by elastic material (e.g. silicone elastomer)
- Halbach motor configuration – permanent magnet array in rotor - stationary coils in stator – magnetic bearings for frictionless operation
- **Brittleness of magnetic material to hoop stresses suggests use of magnetic composites comprising magnetic powder in a plastic matrix**
- Lunar-sourced magnetic material – **AlNiCo**/Co-ferrite permanent magnets, **silicon steel/silica** soft magnets, **aluminium** wiring and **Ti/glass** wheel structure

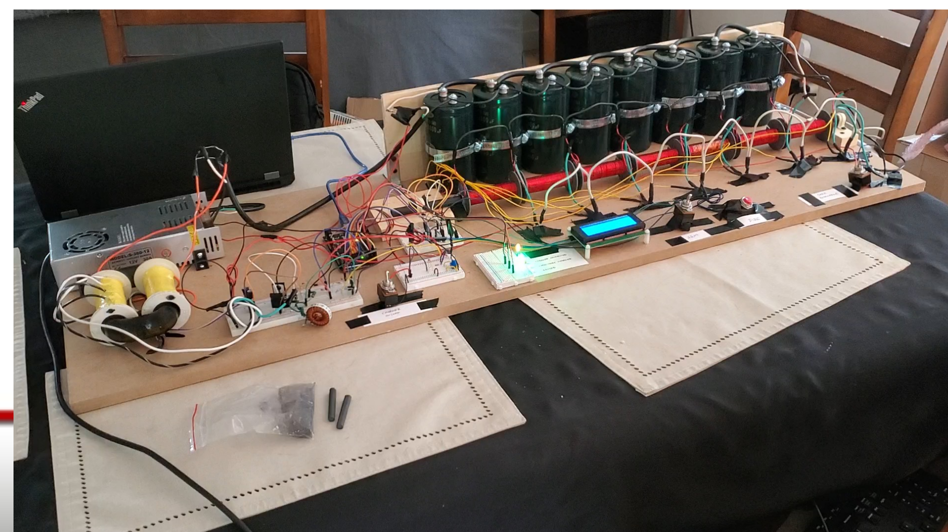
Electromagnetic Launcher

- Rather than burning lunar water (**non-renewable resource**) as propellant/oxidizer, electromagnetic launcher consumes only solar-derived energy
- Electromagnetic launcher – **coilgun is a rolled out linear DC motor**









- Carleton desktop e/m launcher built by Alex Craig-Sheldon

Conclusions

- I believe that we can make self-replication technology a technology of today not tomorrow
- Am I mad as a hatter?
- Answers to:

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