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# The long history...

### Work in collaboration with Alan Dorin (Monash University)

### **Past Visions of Artificial Futures**

One Hundred and Fifty Years under the Spectre of Evolving Machines

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### Abstract

The influence of Artificial Intelligence (AI) and Artificial Life (ALife) technologies upon society, and their potential to fundamentally shape the future evolution of humankind, are topics very much at the forefront of current scientific, governmental and public debate. While these might seem like very modern concerns, they have a long history that is often disregarded in contemporary discourse. Insofar as current debates do acknowledge the history of these ideas, they rarely look back further than the origin of the modern digital computer age in the 1940s-50s. In this paper we explore the earlier history of these ideas. We focus in particular on the idea of self-reproducing and evolving machines, and the potential implications for our own species. We show that discussion of these topics arose in the 1860s, within a decade of the publication of Darwin's The Origin of Species, and attracted increasing interest from scientists, novelists and the general public in the early 1900s. After introducing the relevant work from this period, we categorise the various visions presented by these authors of the future implications of evolving machines for humanity. We suggest that current debates of the co-evolution of society and technology can be enriched by a proper appreciation of the long history of the ideas involved.

Introduction

Manchester, the narrator raises the idea of *machines making machines* and alludes to the profound potential of such a development (see quote above).

During the same period, the scientific understanding of the complexity of biological life was undergoing a revolution, in the theories being developed by Charles Darwin and Alfred Russell Wallace. Both theories were first presented at the Linnean Society of London in 1858 (Darwin and Wallace, 1858), with a greatly extended presentation of Darwin's theory appearing a year later with the publication of The Origin of Species (Darwin, 1859).

At this time, the intellectual elite of England were a richly connected web of thinkers, among whom ideas of science, philosophy, technology, literature and the arts freely flowed. It did not take long for the contemporaneous ideas of machines making machines, and of the evolution of biological organisms, to be connected—the result was the development of the idea of self-reproducing and evolving machines.

In this paper we explore the work of prominent authors of the nineteenth and early twentieth centuries who addressed this topic. We then identify common themes in their work in terms of the implications of these ideas for the future of human society and evolution, and conclude with brief comThe Spectre of Self-Reproducing Machines

An Early History of Evolving Robots

Tim Taylor & Alan Dorin

New York Times Best Seller!!

Paper at ALIFE 2018

Forthcoming Book!

## The near future...

OEE Workshop Series: Developing a better understanding of open-ended evolution (organized by Mark Bedau, Alastair Channon and me)

### Open-Ended Evolution: Perspectives from the OEE Workshop in York

Abstract We describe the content and outcomes of the First Workshop on Open-Ended Evolution: Recent Progress and Future Milestones (OEE1), held during the ECAL 2015 conference at the University of York, UK, in July 2015. We briefly summarize the content of the workshop's talks, and identify the main themes that emerged from the open discussions. Two important conclusions from the discussions are: (1) the idea of pluralism about OEE-it seems clear that there is more than one interesting and important kind Simon McGregor Motorological of OEE; and (2) the importance of distinguishing observable behavioral ballmarks of systems undergoing OEE from hypothesized underlying mechanisms that explain why a system exhibits those hallmarks. We summarize the different hallmarks and mechanisms discussed during the workshop, and list the specific systems that were Kenneth O. Stanley 55555 highlighted with respect to particular hallmarks and mechanisms. We conclude by identifying some of the most important open research questions about OEE that are apparent in light of the discussions. The York workshop provides a foundation for a follow-up OEE2 workshop taking place at the ALIFE XV conference in Cancún, Mexico, in July 2016. Additional materials from the York workshop, including talk abstracts, presentation slides, and videos of each talk, are available at http://alife.org/ws/oee1.

Tim Taylor\*† Mark Bedau<sup>‡</sup> Alastair Channon§ David Ackley<sup>††</sup> Wolfgang Banzhaf<sup>‡‡</sup> Guillaume Beslon<sup>§§</sup> Emily Dolson totals Tom Froese<sup>†††</sup> Simon Hickinbotham<sup>‡</sup> Takashi Ikegami<sup>‡‡‡</sup> Barry McMullin 888 Norman Packard 1000(0) Steen Rasmussen<sup>††††</sup> Nathaniel Virgo### Eran Agmon 9999 Edward Clark<sup>†</sup> Charles Ofria 1000 Glen Ropella<sup>†††††</sup> Lee Spector !!!!! Adam Stanton§ Christopher Timperley Anya Vostinar Michael Wiser

### Keywords

erpetual novelty, adaptive evolution, dynamical

00 This paper was primarily written by the first three co-authors [T.T., M.B., A.C.] based upon material presented and discussed by participants of the First Workshop on Open-Ended Evolution (OEEI) during the European Conference on Artificial Life 2015 at the University of York, UK, Additional material and comments were provided by the other presenters at the workshop [D.A. W.B., GB., E.D., T.F., S.H., T.L. B.M., N.P., S.R., and N.V.I and by the other coauthors, who contributed to discussions at the workshop or afterwards online Ontact author

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- # University of New Mexico USA
- ## Memorial University of Newfoundland, Canada
- AR I Injuneraté de Lyon France



**OEE1 Workshop Report** published in Artificial Life journal [vol 22(3), 2016]

OEE3 at ALIFE 2018 takes place in Tokyo on 25 July 2018

Abstract submission deadline: 14 May!!

http://alife.org/workshops/oee3/

Towards a General Framework for the Study of Open-Ended Evolution

## **OEE Pluralism**

- Lots of different types of systems discussed in first two OEE workshops, e.g.
  - Avida
  - o Geb
  - Novelty Search
  - Patented Technology
- Talk of different types of OEE
- Is it possible (and productive) to consider all of these systems under a single framework?
  - Are there any consistent features shared by all?
  - Is there a "Core" OEE? Or are they really different things?
- My approach: focus first on kinds of requirements as a way to categorise different types of OEE

# Generic requirements (for any OEE system?)

### Four categories:

- A large, and expanding, search space of different forms [EXPANDING TRAIT SPACE]
- Criteria for deciding the value of a given form [SELECTION]
- Method to generate new forms [GENERATION]
- Drive for ongoing exploration of previously unvisited areas of trait space [DRIVE]

### Each of these can be determined either:

- Within the system itself [INTRINSIC]
- By an external mechanism [EXTRINSIC] (predefined, "hard-coded")

	EXPANDING TRAIT SPACE	SELECTION	GENERATION	DRIVE
INTRINSIC	0	0	0	0
EXTRINSIC	1	1	1	1

Each of the 4 requirements can be satisfied either intrinsically or extrinsically, so this framework defines  $2^4 = 16$  types of OEE

• The Biosphere has Type 0 OEE (0000)

Novelty Search has Type 15 OEE (1111)

# **Expanding Trait Space**

- Reparameterisation of the search space (Maley / de Vladar, Santos & Szathmary / etc.)
- Transformational creativity (Boden)
- "New games to play" (Barricelli / Ray / etc.)
- "Door opening events" (Bedau)
- "Watershed events" that "open the floodgates" for new adaptations (Dawkins)
- Distinguish between:
  - New organisation of form (e.g. major transitions) [= GENERATION?]
  - New ways of using existing forms (Wagner's "novelty") [= SELECTION?]
  - Using new properties of the environment (Wagner's "innovation")
- Examples:
  - Making use of new modalities, new sensors and effectors (intrinsic)
  - New fitness functions, staged evolution (extrinsic)

## Selection

- Criteria for deciding the value of a given form
  - Which forms get to survive? Which get to reproduce?
- Always occurs when the form interacts with some kind of external system / environment
  - Interaction of form with environment = behaviour
- The environment may, or may not, be shared by other forms
- Examples:
  - Fitness function (extrinsic)
  - Self-reproductive ability (intrinsic)

## Generation

- Method to generate new forms
- For evolution, will make use of selection operation to determine which forms act as parents
  - But this relationship may be rather indirect in some cases (e.g. Novelty Search)
- Examples include:
  - Self-replication (for intrinsic generation)
  - Mutation (could be intrinsic or extrinsic)
  - Genome rearrangement operators
  - Novelty Search measure of phenotypic distance

## Drive

- Drive for ongoing exploration of previously unvisited areas of trait space
- Distinguish:
  - E xploration of existing trait space
    - novelty (Wagner), combinatorial & exploratory creativity (Boden)
  - Expansion of trait space (a different mechanism)
- Much existing work on theories for intrinsic drive, e.g.
  - Ecosystems / co-evolution
  - Niche construction
  - Environment engineering
  - Population dynamics / drift / adaptive radiations
  - Genotype networks / phenotype networks / neutral networks
- Being far from equilibrium / low entropy another hallmark of OEE?

# Interactions between categories

EXPANDING TRAIT SPACE	SELECTION	GENERATION	DRIVE
• Novelty,	surprise Major t	ransitions • Ev	oEvo
	•	Ecology	
•	Innov	vation	

Taking a step back...

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# If we had a machine that could build more copies of itself...

Then, for a fixed capital outlay (the cost of designing and building *one* machine), we could get exponentially increasing production and returns:

- Harvest for production of valuable materials or energy (at macro-, micro-, or nano-scales)
- Very desirable for mining off Earth (e.g. asteroids, moons) — launch costs massively reduced
- In the far future, a means of allowing humankind to colonise other worlds

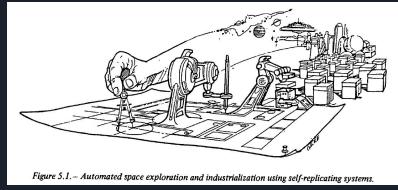


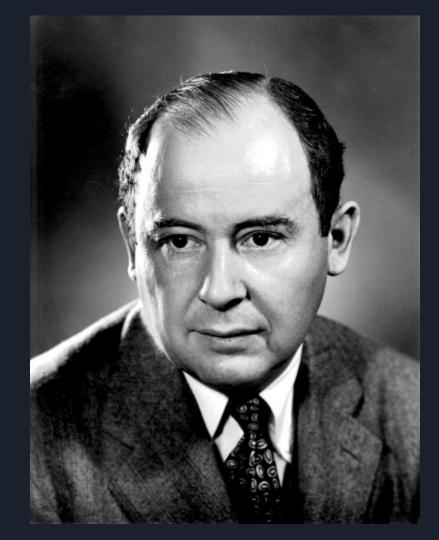
Image from NASA report by Freitas & Gilbreath (1982)

### Commercially tempting, but many risks!

- Causing an environmental disaster
- Mutating and evolving

# The Theory of Self-Reproducing Automata

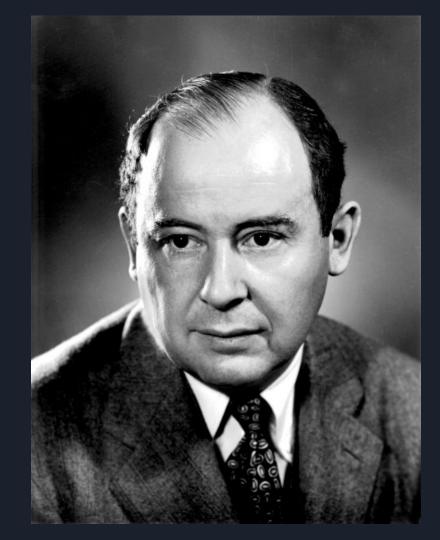
Pick up any book about self-reproducing machines, and they are likely to start with a discussion about this man...



# The Theory of Self-Reproducing Automata

The idea of self-reproducing and evolving machines seems like a very modern concern, but when did people first start thinking about these things?

(We'll come back to von Neumann later!)



Let's play Numberwang!

"Oh my goodness, shut me down! Machines making machines — how perverse!"

C-3PO Star Wars: Episode II Attack of the Clones (2002) "And why should one say that the machine does not live?... It breathes... It moves... And has is not a voice?... And yet the mystery of mysteries is to view machines making machines; a spectacle that fills the mind with curious, and even awful, speculation"

Benjamin Disraeli Coningsby (1844) "We realized that the true problem, the true difficulty, and where the greatest potential is — is building the machine that makes the machine"

Elon Musk Tesla Annual Shareholder Meeting (2016) "I think ... that this is the end ... of man ... But not the end of evolution. The children of men still live — the machines will go on. Not of man's flesh, but of a better flesh, a flesh that knows no sickness, and no decay, a flesh that spends no thousands of years in advancing a step in its full evolution, but overnight leaps ahead to new heights."

John W. Campbell The Last Evolution (1932)

"I knew that baby meant we are more than just slaves. If a baby can come from one of us, we are our own masters."

Freysa (a Nexus-8 replicant) Blade Runner 2049 (2017) The (very) early history of the idea of self-reproducing machines

# Four major steps in the development of the idea of self-reproducing machines

- The idea that animals can be understood as machines → so some machines can reproduce?
   Rene Descartes (1630s-1640s)
- 2. The idea that animals have evolved Charles Darwin (1859)
- 3. The idea that machines, like animals, could evolve Samuel Butler (1863)
- 4. Development of rigorous theory & practical implementations of self-reproducing machines John von Neumann (c. 1948), Nils Barricelli (1953), Lionel Penrose (1957)

# Step 1: The idea of animals as machines

"Do you say that beasts are machines just as watches are? Put a male dog-machine and a female dog-machine side by side, and eventually a third little machine will be the result, whereas two watches will lie side by side all their lives without ever producing a third watch."

Bernard Le Bovier de Fontenelle, *Letter XI "to Monsieur C…"* (1683)

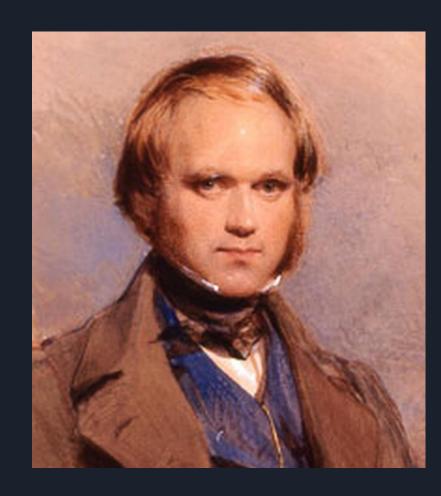


# Step 2: The idea that animals evolve

The melting pot of London in the mid-1800s: Intellectual society was a rich web of social, professional and family connections

Darwin ~ Babbage ~ Lovelace ~ Byron ~ Shelley ~ Butler ~ Marshall ~ Paley ~ ....

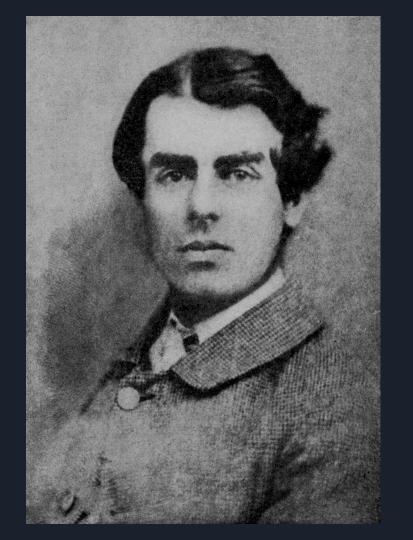
The publication of *The Origin of Species* came shortly after the climax of Britain's Industrial Revolution...



Step 3: The idea that machines can evolve

# Samuel Butler (1835-1902)

- Emigrated from England to New Zealand in 1859
- Read The Origin of Species shortly after arriving
- Inspired many of his works:
  - Darwin Among the Machines (1863)
  - Lucubratio Ebria (1865)
  - The Mechanical Creation (1865)
  - Erewhon (1872)



### THEPRESS

" Nhi stile quot can becestum."

Voc. III.-No. 192

SATURDAY, JUNE 15, 1862,

PERCENTED DATES-PRICE NO.

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### THEPRESS

" Nihil utile quod non honestum."

Vot. III.-No. 192

SATURDAY, JUNE 13, 1863.

PUBLISHED DAILY-PRICE 3D.

### Correspondence.

### DARWIN AMONG THE MACHINES.

TO THE EDITOR OF THE PRESS.

SIR,-There are few things of which the present generation is more justly proud than of the wonderful improvements which are daily taking place in all sorts of mechanical appliances. And indeed it is matter for great congratulation on many grounds. It is unnecessary to mention these here, for they are sufficiently obvious; our present business lies with considerations which may somewhat tend to humble our pride, and to make us think seriously of the future prospects of the

# Samuel Butler Darwin Among the Machines

- Machines are being endowed with increasingly sophisticated powers of self-regulation and self-acting
- Freed from constraints of feelings and emotions, machines will become "the acme of all that the best and wisest man can ever dare to aim at"
- Machines will still be reliant upon humans for feeding them, repairing them and producing their offspring. However ...

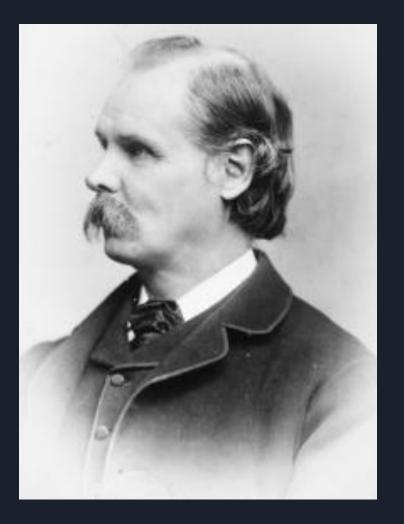
"it is true that machinery is even at this present time employed in begetting machinery, in becoming the parent of machines"

"the reproductive organs of the machines [might become] developed in a manner which we are hardly yet able to conceive"

Samuel Butler, Darwin Among the Machines (1863)

# Alfred Marshall (1842-1924)

- Well known in his later career as a founding father of neoclassical economics
- In early career, presented a series of lectures at a philosophical discussion club at Cambridge University (~1867)
  - Exploring how far it was possible to account for human behaviour in purely physical terms
  - The third lecture was entitled "Ye Machine"
  - Discussed basic designs for a machine (a robot) that could learn from experience



"Nay, further, the Machine . . . might make others like itself. We thus get hereditary and accumulated instinct. For these descendants, as they may be called, may vary slightly, owing to accidental circumstances, from the parent. Those which were most suited to the environment would supply themselves most easily with fuel, etc. and have the greatest chance of prolonged activity. The principle of natural selection, which indeed involves only purely mechanical agencies, would thus be in full operation."

Alfred Marshall, Ye Machine (1867)

# Early American pulp science fiction (late 1920s onwards)



to unimagined heights of mathematical complexity?

Even the popular belief that two and two make four might not be left unchallenged. All that is certainly known is that they have done so very frequently. The rule is not therefore Brighton gathering of the previous year, by a casual allusion to "the two obvious fallacies in the theory of relaproved to be invariable, nor, could it be shown that it has been so in the past, would it be a logical consequence that it must be always so in the fucian to be disregarded and the scien-tific world had waited impatiently for a justification of that audacious chalture. But Dr. Tilwin made no further

lenge, which had appeared only a few weeks earlier, and concerning which none of the nine persons in English and bib stronghold.

who professed (rightly or not) to un-derstand the assunited theory had the attention of his audicibe to the yet ventured an opinion.

Now it was hoped that the new set the state of modern scientifie discoveries so they had materialized themselves in the changed conditions of human a further elucidation of the startling life, and then, more specifically, as



Author of "The Black Star Passes," "Invaders from

IT must be the dream of countless numbers to reach the seme of spolution which, quite likely, would bring with it nearly everlasting life and remarkable progress-but how many, we wonder, would be willing to fureye their human weaknesses to attain the highest state as it is visially portraved by our young author, marvelous as such a degree of evolution unquestionably is:

### Ubstratol by MOREY

AN to be start goes arrives the fact the very sense and a regulation that some other System. I tense and the absolute grapher, in the same that the original period south of complete, so when the contract in memory, over the struggle for the System, and and Elizabe in 2002.

It is also shown that the contraction of the structure of the structure of the contraction of the structure of the structur

could in the other large district and the could be compared from the other large district and the could be considered, and it could be conside

So I am netting done, my record on the mental/pe.

So I am netting done my record on the mental/pe.

Will distribute higher higher light and productions of the mental/pe.

Will distribute higher hig En en 25 de parte de la tre de la companya del la companya de la companya del la companya de la companya del la companya de la companya del la companya del

THE MACHINE

The author of "Twilight" tells of a day of horror and darkness on Earth -and of the light that followed it

by Don A. Stuart

Illustrated by Elliot Dold

THE SUN was beginning to "Aies Falcor, please, Aies Falcor, lower from the meridian as Tal please."

Mason stretched and rose from the seperiment, He stepped out on the it. Also appeared, slins in white and

baleony and looked off across the city, then back at the experimental material the room. They had time to learn grace and case then. The Machine did everyhalf smilingly, half rucfully, thing else. She smiled as she glanced at thought, smiling; "that is, if I did it the screen, right. The Machine did it twenty years "Tal-w

simple in silvery-gray and velvet black the sunlight as they dived or swam, most

Something hummed softly, and Tal

"Aies Falcor-RXDG-NY."

swirled into moving color. A room,

black, simple, comfortable furnishings. A soft, musical voice was calling:

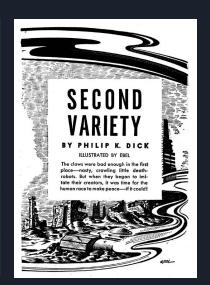
"Tal-was the Machine wrong?" Her golden brown face laughed at him For some ten minutes he stood look-"Is it ever?" he asked. "I wondered whether you were there. I thought you ing off across the green and silver patchwork, the green of the trees and might have joined the games."

gardens, the silver beacons of the slim
A slight frown of annoyance crossed healdings, the flashing silver of machines. Tiny bright spletchies of color
sistent I go with him to Kaim-so-I chines. Tiny bright splotteles of color bere and there marked the people, people in red and gold and blue, in "I'd rather you came here. I finishe "I'd rather you came here. I finished rainbows and in clear white, stroning, running, flaving, resting. Never work in go of coarse. The Machine did that, not floating—flying. I wish you'd see to his apartment, it. It will function, even."

went through the laboratory to the liv-ing room, and sat down at the televisor the colors faded from the screen as Tal him some two hundred feet down A The hum changed slightly, then soft group of some two dozen men and clicks sounded as the frosted screen women were playing about a poel. Their skins flashed pink and bronze in

metal, with spots of gold against the were lying about listlessly.

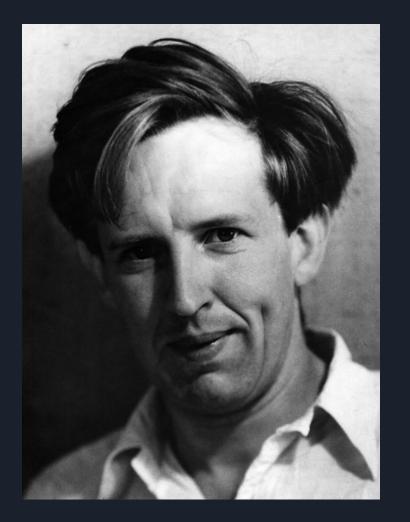
Tal turned away in annoyance. He knew some of those people. Beauty is



Many early sci-fi stories involving self-reproducing and evolving machines! These are just a few examples

# John Desmond Bernal (1901-1971)

- Well known in his later career for pioneering work in structural crystallography
- Also wrote many papers on science and society
- The first of these was "The World, the Flesh and the Devil" (1929)
  - Explored what we might predict about the future of humanity
  - Including space colonisation in "Bernal spheres"



"As the globes multiplied they would undoubtedly develop very differently according to their construction and to the tendencies of their colonists, and at the same time they would compete increasingly both for the sunlight which kept them alive and for the asteroidal and meteoric matter which enabled them to grow. Sooner or later this pressure... would force some more adventurous colony to set out beyond the bounds of the solar system."

J. D. Bernal, The World, The Flesh and the Devil (1929)

The "Cambrian Explosion" of self-reproducing robots (1940s-1950s)

# The Theory of Self-Reproducing Automata

John von Neumann put the subject on a firm theoretical grounding in late 1940s - early 1950s

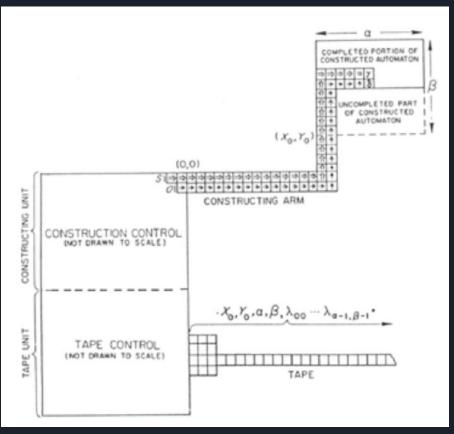
Showed it was logically possible to build a machine that could build another copy of itself...

...or that could build something more complicated than itself

Proposed an architecture for a self-reproducing machine:

Similar to biological genetic architecture with information tape, decoder, constructor, ....Quite complex!



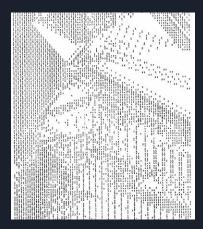


Schematic of von Neumann's Cellular Automata implementation of a Self-Reproducing Machine (estimated size of full implementation = 200,000 cells!)

# First implementations

In software

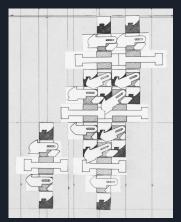
Nils Aall Barricelli (1953) In von Neumann's group at IAS, Princeton

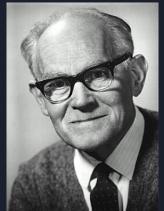




In hardware

Lionel Penrose (1957) At UCL, London





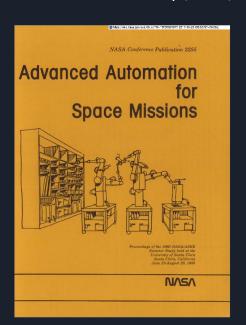
But these are "bottom-up", not "top-down", approaches!

## More recent work

NASA Study (1980)

Foresight guidelines (2000-)

And continuing work...





### Affordable, Rapid Bootstrapping of the Space Industry and Solar System Civilization

Philip T. Metzger, Ph.D., A.M.ASCE<sup>1</sup>; Anthony Muscatello, Ph.D.<sup>2</sup>; Robert P. Mueller, A.M.ASCE<sup>3</sup>; and James Mantovani. Ph.D.\*

Abstract: Advances in robotics and additive manufacturing have become game changing for the prospects of space industry. It has become feasible to bootstrap a self-sustaining, self-expanding industry at reasonably low cost. Simple modeling was developed to identify the main parameters of successful bootstrapping. This indicates that bootstrapping can be achieved with as little as 12 t landed on the Moon during period of about 20 years. The extripment will be telepressed and then transitioned to full autonomy so the industry can seread to the asteroid belt and beyond. The strategy begins with a subreplicating system and evolves toward full self-sustainability (full closure) via an in situ technology spiral. The industry grows exponentially because of the free real estate, energy, and material resources of space. The mass of industrial assets at the end of bookstapping will be 156 t with 60 humanoid robots or as high as 40,000 t with an many as 100,000 humanoid. robots if faster manufacturing is supported by launching a total of 41 tto the Moon. Within another few decades with no further investment, it can have millions of times the industrial capacity of the United States. Modeling over vide parameter ranges indicates this is reasonable, but further analysis is needed. This inclusive receives to resolutive the horses condition DOI: 10.1061//ASCEDAS.1943-555.0000336. D. 20/3

CE Database subject headings: Vasafactories Robotics Moon Space colonies Space embracion Mining Author knywords: ISRU; Space manufacturing; Robotics; Space resources; Lunar industry; In situ resource utilization; Settling space;

Stace colonization: Stace exploration: Stace mining.

The solar system's resources are the key to humanity's future. This willington's demand for energy and material resources is rapidly that these limits are beginning to be felt in some of the noncenewable energy and mineral resources (Bentley 2002; de Almeida and Silva-2009; Lin and Liu 2010; Modd and Ward 2008; and that they cannot support current rates of population growth with industrialization for another century. Fortunately, the processes that formed a habitable that halso endowed the solar evitien with literally billions of times more resources than exist on one planet alone (Hastmann 1985; Lowis and Louis 1987; Licenser 1993; Duke et al. 2006; Mueller

Physicist, Granular Mechanics and Regolith Operations Laboratory.

Physical Cornels Machanics and Rapidith (Sprains Laborany, Markan Jonosoules, and Sprain Alleniandes, ASAS) Normally Sprain Alleniandes, and ASAS (Normally Sprains) Askard Asamanics, and Sprain Alleniandes, and Laborane, and Asamanica Cornels, and Rapid Talengary George of Charter, Alphone (Sandard Armanics, and Sprain Alleniandes) Asamanica (Sandard Armanics) Asamanica (Laborandes) Asam

to A Manicular man gov Note. This manuscript was submitted on November 15, 2011; approved ogen seen some 1, 2015; separate decreasions must be submitted for infl-vidual papers. This paper is part of the Journal of Aerospa or Engineering. Vol. 20, No. 1, January 1, 2013. GASCE, ISSN 0893-1321/2013/1-18-2-9-201-09.

resources for the benefit of humanity.

Until now this has not been economically feasible because of the vast distances and orbital energies separating the bodies in this sola system with the high expense of spaceflight. O'Noil (1989) estimated in the 1980s that an orbiting space colony could become economic only if it had a human population of greater than 10,000 to perform manufacturing tasks. History has since proven that there was little chance of building a space colony if it had to be that large to make a profit. Zubin (1999) argued in the 1990s that human-tended manufacturing colonies on the Moon or in the asteroid main belt were not practical because the massive energy needed to grow food for the humans and because of the scarcity (in the lanar case) of some elements such as hydrogen, nitrogen, and carbon. In their analysis, O'Neilland Zebrin did not include the effects of sobotic laborers in lies of humans to lower the costs, mobably because robotic technology was too imparate to peedict with any confidence. (Similarly, the current study ignores the possible effects of muotechnology.) Since then. advances in relative and additive manufacturing (throughmentional attempted to demonstrate in this paper-to bootstrap a self-sustaining self-expanding long industry that will spread across the solar system at no further expense to the Earth's economy. Another game changer is the discovery of transpolarics, providing vast quantities of hydrogen, nitrogen, and carbon. The Moon has every element needed for healthy industry. In light of these game-changing advances and discoveries, it Simportant to reassess the prospects for initiating space industry.

Once successfully bootstrapped, a robotic network can access process, transport, and use the solar system's resources for human kind's benefit. Appropriately designed robots will not have the problems traveling the vast distances of the solar system that human

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# What use is history?

- Intellectual context and assumptions
  - The idea of what an organism is
  - The idea of how reproduction works
- Approaches to self-reproduction
  - o Top-down vs bottom-up
- Purpose and goals
  - Scientific
  - Commercial
  - Sociological
- Recurring themes and concerns (ALife & Society paper, Al safety, etc)
  - Takeover by intelligent machines
  - o Implications for human evolution
  - Implications for human society

# Some interesting recent references:

Gunter Wagner "Evolutionary innovations and novelties: Let us get down to business!" Zoologischer Anzeiger 256 (2015) 75-81

Harold de Vladar, Mauro Santos and Eors Szathmary "Grand Views of Evolution" Trends in Ecology & Evolution (2017)

Tim Taylor and Alan Dorin "Past Visions of Artificial Futures: One Hundred and Fifty Years under the Spectre of Evolving Machines" Proceedings of ALIFE 2018 (to appear)