An Afterword to *Rise of the Self-Replicators*: Placing John A. Etzler, Frigyes Karinthy, Fred Stahl, and Others in the Early History of Thought About Self-Reproducing Machines

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Abstract This article is an afterword to the book *Rise of the Self-Replicators: Early Visions of Machines, AI and Robots That Can Reproduce and Evolve*, coauthored by Tim Taylor and Alan Dorin (2020). The book covered the early history of thought about self-reproducing and evolving machines, from initial speculations in the 17th century up to the early 1960s (from which point onward the more recent history is already well covered elsewhere). This article supplements the material discussed in the book by presenting several relevant sources that have come to the author's attention since the book was published. The most significant additions to the history are from the German-born, 19th-century inventor and utopian John Adolphus Etzler in the 1830s–1840s, the Hungarian author and satirist Frigyes Karinthy in 1916, and the U.S. mathematician and computer scientist Fred Stahl in 1960.

1 Introduction

In 2020, Alan Dorin and I published the book *Rise of the Self-Replicators*, in which we discussed the early history of thought about machines, artificial intelligence (AI), and robots that can reproduce and evolve (Taylor & Dorin, 2020). One of the central figures in the book is Samuel Butler, the 19th-century author who explored themes of machine self-reproduction and the evolution of machine intelligence in various works, culminating in his 1872 novel *Erewhon*. Butler (1901) later published a sequel, *Erewhon Revisited*, in which the narrator comments at one point, "It has been said that though God cannot alter the past, historians can" (p. 169). Taking my lead from Butler, in this afterword to *Rise of the Self-Replicators*, I wish to alter our history of self-reproducing machines by adding some discussion of several sources of early thought about self-reproducing and evolving machines that have come to my attention since the book's publication.

The bulk of our survey in *Rise of the Self-Replicators* is presented chronologically over four chapters of the book: Chapter 3, "Babbage Meets Darwin: Mechanisation and Evolution in the 19th

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Century"; Chapter 4, "Robot Evolution and the Fate of Humanity: Pop Culture and Futurology in the Early 20th Century"; Chapter 5, "From Idea to Reality: Designing and Building Self-Reproducing Machines in the Mid-20th Century"; and Chapter 6, "More Recent Developments: Signposts to Work from the 1960s to the Present." I stick to this structure in the following three sections, discussing newly discovered material that belongs to chapters 3, 4, and 6 of the book, respectively (I report no new content for chapter 5).

2 "Babbage Meets Darwin: Mechanization and Evolution in the 19th Century"

Chapter 3 of *Rise of the Self-Replicators* covers the first extended explorations of the idea of self-reproducing machines in the 1800s. The growth of interest in the topic at that time was spurred by two factors: the climax of the British Industrial Revolution in the first decades of that century and the publication of Charles Darwin's (1859) *On the Origin of Species*. Although most of the work discussed in the chapter is from the 1860s onward and was influenced by both of these factors, the extract from Benjamin Disraeli's 1844 novel *Coningsby* quoted at the start of the chapter—and repeated here—demonstrates that, even before Darwin introduced his idea of evolution by natural selection, the increasing complexity and manufacturing capabilities of machines emerging in the Industrial Revolution were in themselves sufficient to elicit the idea of a self-reproducing machine in some future thinkers:

> And why should one say that the machine does not live? It breathes. … It moves. … And has it 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. (Disraeli, 1844, p. 154)

Undoubtedly one of the most significant bodies of work I have come across since writing *Rise of the Self-Replicators* is that of John Adolphus Etzler, whose contributions over the period from the late 1820s to the early 1850s certainly fall into this category of pre-Darwinian Industrial Revolution thinking.

2.1 John Adolphus Etzler: *The Paradise Within the Reach of All Men* (1833)

Johann Adolph Etzler (hereinafter referred to by the Anglicized form John Adolphus Etzler) was a 19th-century German inventor who would be regarded today as a *techno-utopian*; he believed that machinery could be designed to provide for all human needs, abolishing the need for work and money and leaving people free to pursue their own interests and pleasures.

Despite attracting a significant following during his lifetime, particularly in Great Britain and Germany, Etzler's work has languished in obscurity after his death (the date of which is unknown). Aside from his own writing (e.g., Etzler, 1833, 1841), the most accessible description of his life and work until very recently has been a generally unflattering account presented in American historian Steven Stoll's 2008 book *The Great Delusion: A Mad Inventor, Death in the Tropics, and the Utopian Origins of Economic Growth*. However, a 2021 PhD thesis by James McIntyre of Loughborough University presents many previously unknown primary sources of information about Etzler's life and work and challenges various inaccuracies presented in Stoll's and other earlier accounts.

Born in 1791, Etzler emigrated to the United States in the 1820s and later lived in various other countries, including Great Britain and Venezuela (McIntyre, 2021). After some early experiments with mechanical systems in Pennsylvania in the late 1820s and involvement in an emigration scheme from Germany to the United States to establish a cooperative community assisted by mechanical devices in the early 1830s, he published his most influential work, *The Paradise Within the Reach of All Men* (Etzler, 1833).

In *Paradise*, Etzler presents a utopian vision whereby all humans could be provided with a high standard of living and no need to work. This would leave them free to spend their time as they wish, in learning, culture, socializing, and pleasure. All of this, he claimed, could be accomplished within the space of 10 years. Etzler's idea was, rather than being guided by existing artifacts and their means of manufacture, to instead take a holistic view of people's basic wants and needs and to consider how these might most simply and systematically be fulfilled using a relatively small number of multifunctional machines:

> To imitate minutely all the infinite variety of produces of human industry by machineries, would be an endless, ungrateful, and foolish undertaking. … It would nearly require to invent for every little work of man a particular automaton. This is not my purpose. But the most simple contrivances I could think of, and as few as possible, for producing, not the customary articles of human industry; but all things that may either substitute or surpass the known necessaries, comforts, and luxuries of men, are my objects in view. … My object is, to furnish, by an extremely simple system, all what may be desirable for human life, without taking for pattern any existing things of industry. By abstracting from all what is in existence and fashion, I am enabled to devise means, without any artificial machinery, for producing every thing that man may want for his nurrishment [*sic*], dwelling, garments, furnitures, and articles of fancy and amusements. (Etzler, 1833, p. 62)

Etzler (1841) recognized that the fulfillment of his vision would require superabundant sources of energy that were "imperishable, indefatigable, working … day and night, without food or wages" (p. 1), and that did not in themselves require further human labor to extract and use. Rather than employing the typical power sources of the day, such as steam, coal, or animals, he instead focused on the enormous potential of natural forces: wind, wave, tidal, and solar energy. To produce a continuous output of energy from these intermittent inputs, he also concentrated on designing energy reservoirs, such as water storage towers, to mediate the supply of energy to his machines. His vision was therefore of a postwork world powered by renewable energy.[1]

In *Paradise*, Etzler (1833) gave a brief sketch of the kinds of machines he envisioned for agriculture and for architecture. More details of these and other machines were provided in his later publication *The New World* (Etzler, 1841). The power of machines to easily manufacture multiple copies of their products played an important role in Etzler's vision. In describing how people may spend their time in his postwork society, he says,

> Is he fond of mechanical occupation?—He may exercise his dispositions and talents to an extent beyond the present conceptions; he may form models and moulds, and see the objects multiplied for use and show to any extent, without any further trouble. Is he gifted with talents for drawing, painting, sculptures, &c.?—He needs but to make one model of every figure, and it may then be multiplied to any desired number, by moulds, etching and printing machines. Is he fond of music?—Where could he find more opportunity than in such a life? He may at once delight and be delighted, by performances of his own and in company with other musicians: instruments and means are at his disposal unknown yet; and his compositions may be repeated and multiplied by mechanical plays and machines. (Etzler, 1833, p. 86)

1 As unusual as this was for the time, Etzler's green credentials—from an anachronistic present-day perspective—are somewhat diminished by his lack of consideration of issues relating to the continued supply of raw materials or of the effect of the envisioned widespread development of the land and sea on other species.

Having set out in *Paradise* his vision of what life might be like in a society in which all work is performed by machines, Etzler explained how the requisite number of machines might be built and how the endeavor might be financed:

> And what is the expense for producing such great things?—None, except for the first machineries of very simple construction, and for the first moulds of all things to be artificially made; for the machineries themselves as well as the moulds for casting the materials for use, are to be made by the same machineries, and may then be multiplied to any number required, without any labor or expense. (Etzler, 1833, p. 82)

In other words, Etzler envisaged that these would be self-reproducing machines; specifically, to use the terminology introduced in *Rise of the Self-Replicators*, they would be *maker-replicators* (i.e., machines that could manufacture a wide variety of products, including copies of themselves). He went on to present examples of the finance and revenues involved in creating a society supported by these machines, basing his calculations on an assumed 10-fold annual increase in the number of machines in operation due to their capacity for self-reproduction (Etzler, 1833, p. 101).

Etzler (1833) argued in *Paradise* that the most effective way to get such an endeavor off the ground would be to form an association of members, each of whom must buy at least one share in the enterprise. The association would find a suitable location, with a warm climate and an abundance of natural resources, for developing an initial community according to Etzler's vision. He spent most of the next decade trying to make this happen, in addition to developing designs and models of various proof-of-concept machines.

In 1844 (the same year that Disraeli was writing *Coningsby*, quoted earlier), Etzler—in partnership with the antislavery campaigner Conrad Frederick Stollmeyer—established the Tropical Emigration Society in London. He had been offered a tract of land by the Venezuelan government and intended this to be the site of his first settlement. Over the next three years, the society attracted thousands of paying members across England and sent more than 200 of its members, Etzler included, to Venezuela to establish the settlement. Sadly, the enterprise ended in tragedy with the deaths of at least 23 of the group (McIntyre, 2021, p. 198). Stoll (2008) lays the blame for the venture's failure squarely on Etzler, although McIntyre (2021) convincingly challenges Stoll's account. McIntyre uncovers evidence of Etzler in London and Bogotá in the period after the failure of the Venezuelan venture, but the full picture of his later whereabouts, activities, and death remains unclear.

Etzler's conception of self-reproduction by mechanical devices equipped with molds calls to mind William Paley's earlier image—in his 1802 book *Natural Theology*, discussed in section 2.2 of *Rise of the Self-Replicators*—of a self-reproducing watch comprising "a mechanism, a system of parts, a mould for instance, or a complex adjustment of laths, files, and other tools, evidently and separately calculated for this purpose" (Paley, 1802/2006, p. 11). To some extent, one might view such a design as an analog version of John von Neumann's (1966) seminal architecture for a self-reproducing machine, devised over a century later and discussed at length in *Rise of the Self-Replicators*: the mold being an analog version of the information storage tape and the machine as a whole being able to make copies of any kind of object defined by the supplied mold, and of the mold itself. It's unclear how a machine might contain a mold of itself to achieve self-reproduction, but this difficulty might be alleviated by imagining a collection of these machines, each supplied with different molds to produce different parts of their offspring and with one or more of the machines charged with assembling the various manufactured parts into a complete offspring. The analogy is still only partial, however, as the analog storage of information in the mold and in the design of the machine itself offers an impoverished potential for heritable mutation compared to the digital information storage, copying, and translation processes von Neumann proposed.

Of course, in 1833, Etzler was not specifically thinking about the potential for mutation and evolution of his machines. It is currently unknown whether Etzler was alive in 1859 to witness the publication of *On the Origin of Species*. Darwin's book triggered a heightened interest in the idea of machine self-reproduction, now envisaged with the additional possibilities of mutation and evolution. As discussed in *Rise of the Self-Replicators*, the most significant work on this topic in the late 1800s was by Butler, with other important contributions from George Eliot (1879) and Alfred Marshall (see Raffaelli, 1994).

3 "Robot Evolution and the Fate of Humanity: Pop Culture and Futurology in the Early 20th Century"

As discussed in chapter 4 of *Rise of the Self-Replicators*, by the turn of the 20th century, the topic of machine self-reproduction and evolution was starting to find its way more regularly into popular works of fiction. Examples offered in the book include E. M. Forster's 1909 short story "The Machine Stops," and Karel Čapek's 1920 play *R.U.R.: Rossum's Universal Robots*.

Forster's story, set in a time when human civilization has become dependent on a global machine to provide for all needs, makes reference to the machine's capacity for repairing itself and even evolving new functions but does not explicitly engage with the idea of machine self-reproduction as such.

Čapek's play, on the other hand, *does* explore in more depth the idea of robots being able to build more of themselves in factories without human supervision. Since writing *Rise of the Self-Replicators*, I have become aware of another work from this period that also directly explores the idea of machine self-reproduction, written by the Hungarian author Frigyes Karinthy and published a few years before *R.U.R.*[2]

3.1 Frigyes Karinthy: *Utazás Faremidóba (Voyage to Faremido)* (1916)

Born in Budapest in 1887, Karinthy was a prominent "humorist, parodist, writer of utopias, poet [and] philosopher" (Tabori, 1978, p. 16). In addition to his own writing, he translated a number of important works into Hungarian, including, in 1914, Jonathan Swift's *Gulliver's Travels*. In 1916, a couple of years after that translation, Karinthy published his own novel, *Utazás Faremidóba* (published in English as *Voyage to Faremido*; Karinthy, 1916/1978), which took the form of a continuation of Gulliver's adventures.

Set in 1914 at the onset of World War I, *Voyage to Faremido* begins as Gulliver, escaping a sinking ship in a hydroplane, is plucked from the plane by a "huge bird-shaped mechanism" from which an enchanting music is emanating. He awakens to find himself in a strange land, soon discovering that he has been transported to a distant planet populated by machines like the one that rescued him. The machines are called *solasis* (singular: *solasi*), and Gulliver discerns that the music they play is their form of communication; he eventually learns the language so that he can communicate with them. Nothing is said about the *solasis'* ultimate origin, but there is a vast factory where they manufacture more of themselves, and spare parts for existing machines as well. Gulliver describes the activities in the factory:

> It became evident how these amazing creatures or mechanisms came into being: they themselves manufactured their equals from metals and minerals, and they themselves activated the finished *solasi* through the sources of energy (electric accumulators, steam, gases, etc.) placed within their bodies.
>
> At first glance this method of procreation appeared to be more complex and difficult than the one employed on our globe … but it must be admitted that as far as the end product was concerned, the *solasis'* system was more reliable and thorough. The *solasi* who created or assembled its companion—I must call it a companion because I can hardly call

2 Several works from the early 1900s involve the creation of new forms of life in a test tube and their subsequent evolution, although as these feature biochemical rather than mechanical life-forms, they are out of the scope of the subject matter of *Rise of the Self-Replicators*. Examples include the novel *The Prots: A Weird Romance* by an unknown author using the pseudonym Dudbroke (1903) and *The Greatest Adventure* by Eric Temple Bell, published under his pen name, John Taine (1929).

> it son or child, in view of the fact that each *solasi* is the creation not of two but of six or seven individuals, and these are all of the same sex—such a *solasi* had the opportunity of examining every part thoroughly from the point of view of its practicability and of assembling it without the slightest blemish or functional fault. (Karinthy, 1916/1978, p. 38)

As the quotation demonstrates, Karinthy employs the idea of collective reproduction accomplished by a group of machines. As discussed in *Rise of the Self-Replicators*, this idea had already been considered by Butler in his 1872 novel *Erewhon* (Taylor & Dorin, 2020, p. 22). The collective reproduction Karinthy described is of a simple homogeneous variety, where each of the machines involved in the process is of essentially the same kind. This is the same type of reproduction envisaged by Čapek (1920) in *R.U.R.*, published four years after *Voyage to Faremido*. These and other examples of collective reproduction are discussed in more detail and compared to more monolithic designs of self-reproducing machines in section 7.1.4 of *Rise of the Self-Replicators*.

As far as I am aware, Karinthy's novel is the first significant work to explicitly cover the idea of machine self-reproduction in the early 20th century—indeed, the first since George Eliot's (1879) *Impressions of Theophrastus Such* in the late 19th century.

3.2 Early Pulp Science Fiction (1920s–1950s)

The 1920s saw the birth of the *pulp science fiction* genre, offering cheap, regularly published magazines containing a vast variety of short stories and novellas.

In *Rise of the Self-Replicators*, we identified S. Fowler Wright's 1929 story "Automata" as the earliest example of the genre we had found that features the idea of machine self-reproduction—and self-design—as a central topic. While "Automata" remains the earliest example of the genre of which I am aware that has an explicit focus on the long-term evolution of machines over many eons, I recently came across an earlier work that has a more implicit suggestion of machine self-reproduction: the American writer Edmond Hamilton's 1926 short story "The Metal Giants."

3.2.1 Edmond Hamilton: "The Metal Giants" (1926)

Hamilton's story features a professor of electrochemistry named Detmold who has discovered how to instill an artificial brain with consciousness. The brain was "constructed … of metal, entirely inorganic and lifeless, yet whose atomic structure he claimed was analogous to the atomic structure of a living brain" (Hamilton, 1926, p. 725). Sacked by his university for his outlandish ideas, Detmold continues working on his artificial brain independently. During the following months of development, he augments the brain with arms so that it can interact with the world. After a sudden illness resulting in a period of hospitalization, Detmold returns to his secluded laboratory to find it ransacked and the brain missing. Soon after, he becomes aware of various incidents reported in nearby towns of "metal giants" attacking people and property. Detmold eventually discovers that the brain, which had gained the ability to move by some unknown method, was building these metal giants itself. The giants possessed a degree of autonomous intelligence but were ultimately controlled by the central brain.

So the storyline does not include the self-reproduction of the artificial brain as such, but it comes very close to the idea—there is a suggestion that it had the capacity to do this if it wanted to: "While the [metal giants] undoubtedly had been furnished some portion of intelligence by their master, the metal brain, that master had been careful not to repeat [Detmold's] own mistake and make them powerful enough to revolt against it" (Hamilton, 1926, p. 737). The self-reproduction evoked here—the potential of the artificial brain to create offspring as intelligent as itself—is therefore of a self-designing type, similar to that more prominently featured in Wright's (1929) "Automata" three years later.

In *Rise of the Self-Replicators*, we also highlighted various other pulp sci-fi stories published after "Automata," in the period from the 1930s to the 1950s, that featured ideas of machine self-reproduction and evolution. I have since found a few more examples to add to this list, as outlined in the following sections.

3.2.2 Henry Hasse: "He Who Shrank" (1936)

American author Henry Hasse's 1936 short story "He Who Shrank" is a tale of worlds within worlds, where molecules, atoms, and electrons at one level of existence are made of the galaxies, systems, and planets of the universe below. A scientist creates a potion that makes anyone who takes it continuously shrink, allowing the individual to travel between these universes. The story relates the experiences of the scientist's assistant—the narrator—who is given the potion against his will, as he visits successive universes below his starting point. In one universe, he discovers a race of "bird people" who have fled their planet and are settling on a moon, building a protective metal shell around it. The main planet has been taken over by machines.

The story summons an image much like that described by Eliot (1879) in *Impressions of Theophrastus Such*, of a world run by unconscious machines busily constructing vast cities of grotesque metal structures all around the planet. As well as engaging in construction, the machines were making more machines (Hasse, 1936). Their construction and self-reproduction activities left little room on the planet for their original creators.

The narrator surmises that the machines have evolved from technology originally created by the bird people themselves:

> I tried to picture their civilization as it had been long ago before this thing had come about. I pictured a civilization in which machinery played a very important part. I pictured the development of this machinery until the time when it relieved them of many tasks. I imagined how they must have designed their machines with more and more intricacy, more and more finesse, until only a few persons were needed in control. And then the great day would come, the supreme day, when mechanical parts would take the place of those few. . . . (Hasse, 1936, p. 38)
>
> But it had proven to be a bitter Utopia. They had gone forward blindly and recklessly to achieve it, and unknowingly they had gone a step too far. Somewhere, amid the machines they supposed they had under their control, they were imbued with a spark of intelligence. One of the machines added unto itself—perhaps secretly; built and evolved itself into a terribly efficient unit of inspired intelligence. And guided by that intelligence, other machines were built and came under its control. The rest must have been a matter of course. Revolt and easy victory. (Hasse, 1936, p. 42)

We learn that the machines have achieved space travel, and the narrator wonders whether this planet was not even the bird people's original home—they had perhaps already been through several rounds of fleeing their machines and the machines then following them from one planet to the next. The narrator wonders whether the bird people will eventually find a way to check their spread, or whether the machines will ultimately occupy every planet in the universe.

"He Who Shrank" therefore paints a picture of a supercharged version of the takeover by machines envisaged by Butler, Eliot, and others, where the machines have not only displaced their designers on their home planet but eventually spread across the whole universe. The kind of evolution described is a mixture of machine self-reproduction and self-design of new types by a master intelligent machine—like the design of new machines by Hamilton's (1926) artificial brain in "The Metal Giants" with the additional capacity for self-reproduction and evolution.

3.2.3 Other Early Pulp Sci-Fi Works (1940s–1960s)

Another work from the period that I have come across since writing *Rise of the Self-Replicators* is "The Mechanical Mice" (Hugi, 1941).[3] This short story features a "Robot Mother" that sends out

3 The story was published with Hugi as the author. There are various accounts of the extent to which it was written by Hugi or by his friend Eric Frank Russell, who was a much more successful British sci-fi author (see Ingham, 2010, pp. 157–159).

workers (mechanical mice) to collect raw materials that it needs to reproduce itself. This system is likened to a bee colony, with workers, warriors, a drone, and a queen, much as Butler (1872), in *Erewhon*, used analogies of bee/flower pollination systems and ant colonies for collective reproduction in machines (see section 7.1.4 of *Rise of the Self-Replicators*).

One more story deserves a quick mention in this section: "Two-Handed Engine"[4] by C. L. Moore and Henry Kuttner (1955/2019). The story is set on a future Earth after human society collapsed in the late 20th century due to an overreliance on machines resulting in a breakdown of social and emotional bonds between humans. Across the world, humankind had been brought to a state of anarchy. The machines, however, fared better in this period:

> Some of their species were wiped out entirely and left no machines to breed and reproduce their kind. But most of them minded their raw materials, refined them, poured and cast the needed parts, made their own fuel, repaired their own injuries and maintained their breed upon the face of the earth with an efficiency man never even approached. (pp. 281–282)

One unusual aspect of the plot of "Two-Handed Engine" is that the machines are entrusted with saving human society—by acting as a police force—rather than the more common plot line of machines taking over the world.

I expect that there are other relevant stories from this period, especially from the 1950s onward. By the 1960s, the concepts of machine self-reproduction and evolution were becoming common themes. As noted in *Rise of the Self-Replicators*, some of the most significant examples from the 1960s include Poul Anderson's 1962 short story "Epilogue," Stanisław Lem's 1964 novel *Niezwyciężony* (published in English as *The Invincible*; 1973), Fred Saberhagen's Berserker series (commencing with *Berserker* in 1967), and John Sladek's 1968 novel *The Reproductive System*.

One further example deserving a place in this list is the novel *Sagan om den stora datamaskinen* (published in English as *The Tale of the Big Computer*) by the Swedish physicist Hannes Alfvén, written under the pen name Olof Johannesson (1966/1968). Although it was published a few years after the period of early pulp sci-fi on which we concentrated in *Rise of the Self-Replicators* (i.e., the 1920s–1950s), I will say a few words about it here because of its unusual status of being written by a scientist who not only was a Nobel laureate but also had very likely met von Neumann.

The story foresees the increasing role of computers in all aspects of human life, particularly in organizing the complex systems of government and society. Eventually it is deemed more reliable to have computers rather than humans in charge of their own maintenance, to which end a self-reproducing supercomputer is designed. Alfvén envisaged reproduction of the maker-replicator type, that is, a machine that can produce other types of machines and reproduce itself, as von Neumann (1966) originally proposed.

It is unclear whether Alfvén was directly influenced by von Neumann's work, but von Neumann had visited Alfvén's home department at the Royal Institute of Technology in Stockholm in 1954 (Dyson, 2012, p. 305), so it is possible that they discussed the topic then. *The Tale of the Big Computer* (Johannesson 1966/1968) is noteworthy for its many visions of future technology that have indeed come to pass, including home computers, smartwatches and fitness trackers, working from home, internet shopping, and neuroprosthetics, to name a few.

More recent examples of self-reproducing machines in fiction, from the late 1960s onward, are numerous but are beyond the scope of our early history of the topic.[5]

4 The title is a reference to the enigmatic lines in John Milton's 1637 poem "Lycidas": "But that two-handed engine at the door / Stands ready to smite once, and smite no more."

5 As stated in *Rise of the Self-Replicators*, a partial—yet extensive—list of self-reproducing machines in fiction can be found on Wikipedia at https://en.wikipedia.org/wiki/Self-replicating_machines_in_fiction.

4 "More Recent Developments: Signposts to Work From the 1960s to the Present"

In chapter 6 of *Rise of the Self-Replicators*, we provide a brief overview of work on the theory and practice of self-reproducing and evolving machines from the 1960s onward. As most of this work has been well covered by other histories of the subject, we restricted ourselves to highlighting some of the most significant work and providing details of existing reviews where further information may be obtained.

In our discussion of developments in software implementations in section 6.2 of the book, we talk about the impact of Tom Ray's (1991) Tierra system, in which self-reproducing computer programs compete and evolve. Tierra can be regarded as belonging to a lineage of work on self-reproducing computer programs dating back to the Darwin system ("Computer recreations: Darwin," 1972) developed by V. A. Vyssotsky and colleagues at Bell Labs in 1961.[6] This lineage has been described elsewhere (e.g., Banzhaf and McMullin, 2012) and was therefore not covered in *Rise of the Self-Replicators*. However, in the time since the book's publication, I have become aware of an earlier example of work in this lineage of self-reproducing computer programs, by the American engineer Fred Stahl in 1960, that deserves some attention.[7]

4.1 Fred Stahl on "Artificial Universes"

In the late 1950s, Stahl—a math major at Wayne State University, Detroit—worked part-time in the university's Computation Laboratory to fund his studies (F. G. Stahl, 2013a). As a 16-year-old in 1955, he had already come across John Kemeny's article in *Scientific American* describing von Neumann's work on self-reproducing automata (Kemeny, 1955), and in 1959, he read Lionel Penrose's article about his physical model of self-reproduction (Penrose, 1959) in the same magazine. Combining these sources of inspiration, Stahl (2013a) envisaged

> a *digital* simulation of an extended concept of von Neumann's notional machine. If I could make my creatures mobile in a digital universe with others of its species then I might have lethal competition. If, as von Neumann had conceived, I included digital mutation in reproduction and if the digital entities could kill and eat each other then I would have survival of the fittest. "Life" in the universe would be Darwinian. With luck I might even observe a little evolution. (p. 4)

Working on the lab's IBM Type 650 computer when it was not otherwise in use, Stahl designed and coded an "artificial universe," completing the implementation in February 1960. The universe comprised a linear sequence of 1,350 10-digit words, with the two ends connected to form a circular topology. Multiple programs could live in this environment, being processed in pseudo-parallel by the system's "virtual CPU." Stahl (2013b) explained that "the functions used to define the creature are essentially equivalent to the operation codes of the host computer augmented by an imperfect STORE operation [to introduce mutations] and a special birth operation. Otherwise almost all of the arithmetic, logical, control and input-output (via punch cards) operations are included" (p. 3). The virtual CPU also implemented the death criteria for the programs: If, when executing a creature's code, the CPU came across a zero word (all 10 digits of the word were zero) or an undefined operation, execution of the program ceased.

6 The submission letter, signed by M. D. McIlroy, R. Morris, and V. A. Vyssotsky, and supplementary materials are available at https://www.cs.dartmouth.edu/~doug/darwin.pdf.

7 Fred Stahl is no relation to Walter Stahl (F. G. Stahl, personal communication, 2020), who also published work on simulating self-organization and self-reproduction of artificial cells in the 1960s (e.g., W. R. Stahl, 1965, 1967). Walter Stahl's impressive work, conducted over the mid- to late 1960s, is outside of the time period covered by our history and has been referenced in various other histories (e.g., Langton, 1989), so we do not cover his contributions in *Rise of the Self-Replicators*.

Stahl (2013b, p. 2) created a handwritten self-replicating program with which to inoculate the universe. When executed, the program would perform the following operations in order: (a) move forward one space in the universe; (b) if it encountered a unit of matter (a nonzero word) immediately in front of it, increment its counter of the number of units of matter encountered; and (c) if it had accumulated enough units of matter to equal its size, iteratively copy itself one word at a time to the space behind it before each subsequent movement until a copy of the whole program had been created.

In February 1960, the system was complete and ready to run. The results, however, were disappointing. Initializing the system by distributing random matter (nonzero words) across the space and introducing a single self-replicating program, Stahl reported that the the logs showed that a second program had been born and that both parent and offspring were crawling and "eating" (i.e., crawling over matter). However, when Creature 1 started producing a second offspring, this was eaten by Creature 2 before it was fully created, and some time later Creature 2 took a lethal bite out of Creature 1. At that point, only Creature 2 survived, but it turned out to be a sterile mutant that ate and crawled but produced no offspring (F. G. Stahl, 2013b, p. 4).

Stahl discussed some reasons for the disappointing results, including technical issues such as the need for a larger universe, more creatures, and a faster computer. In terms of the system's design, he pointed out that the mutation rate should be optimized, and also that the conservation of matter should be enforced; the latter, however, would require a significant redesign of the system. Related to the lack of conservation of matter, it could also be noted that the concept of having to "eat" matter to reproduce was not inherent to the "laws of physics" of the universe but was just coded into the original creature itself; it would be perfectly possible to design a creature in the system that reproduced without first collecting matter.

Stahl discussed the system with the head of the Computation Laboratory and a professor of the university's biology department, but the latter did not show any interest in the project, and so Stahl moved on to other things (F. G. Stahl, 2013a, p. 5).

Looking back at Stahl's results now, there is certainly a feeling of "if only" he had tried this or that small modification. Just by lowering the mutation rate, for example, Creature 1 might have had a chance of producing multiple exact copies of itself in the universe so that the birth of a sterile mutant wouldn't necessarily mean the collapse of the whole population.

Still, it is interesting to compare Stahl's design with what came later. Banzhaf and McMullin (2012) provided a concise discussion of the lineage of work on artificial universes with self-reproducing computer programs, covering Vyssotsky's Darwin system ("Computer recreations: Darwin," 1972), Dewdney's (1984) Core War game, Rasmussen et al.'s (1990) Venus Coreworld, and Ray's (1991) Tierra.[8]

We might also add into this lineage work by the Austrian computer scientist Veith Risak (1972), who proposed architectures for the self-reproduction of complex computer programs using information compression and functional equivalence to reduce the amount of information required to be transmitted from parent to offspring. Risak's paper included a description of an implementation of a reproduce-by-copy program (the simplest of the schemes for reproduction discussed in his paper and the same approach as used in Darwin and the other systems listed above) in assembly language on a Siemens 4004 computer.

Self-reproducing programs in the Darwin system and in Risak's work were implemented in native machine code, which had an advantage of speed but also introduced various difficulties. In contrast, Core War and systems after that used their own machine languages designed for the task, interpreted by a virtual computer. Stahl's system, created before Darwin, also used the virtual computer approach and was therefore the first to do so. Darwin, Risak's work, and Core War also lacked a mechanism for evolution through mutation—this was introduced in Venus and Tierra in 1990, but we see that Stahl's system already featured a mutation mechanism in 1960. Several important

8 Steven Levy (1992, p. 221) reports that Ray completed *Tierra* in January 1990. He presented it at the Artificial Life II workshop the following month, although the proceedings were not published until 1991.

aspects of Stahl's design were therefore ahead of their time in terms of allowing for programs that could both reproduce and evolve.

4.2 A Note on Quines, Hamish Dewar, and Jürgen Kraus

As the focus of *Rise of the Self-Replicators* and this afterword is on work done prior to the early 1960s, it is beyond our scope to explore the later history in detail, the logic being that other sources already do a good job at covering this. I will, however, just very briefly mention another flavor of work on self-reproducing computer programs that developed after this period: This focused on programs written in high-level languages (rather than assembly language) that were able to print a copy of their own source code—these programs are called *quines*.[9]

The first quine is attributed to Hamish Dewar at Edinburgh University, written in the IMP programming language. I had an email exchange with Dewar in January 2021 in which he confirmed that, although his "memory of those days is fairly dim now," his quine was written in "the late 1960s." As for his inspiration for writing it, he reported, "My curiosity was probably sparked by someone posing the question of whether such a program was possible or not in the coffee room one day. There was no influence from biological reproduction or anything like that."

The subject of quines reached a larger audience in the 1970s with the publication of a short paper by Paul Bratley (a former colleague of Dewar) and Jean Millo in 1972, which featured implementations in four different languages (SNOBOL, LISP, FORTRAN, and ALGOL) (Bratley & Millo, 1972). Bratley and Millo pointed out that the general structure of the various self-reproducing programs they had presented comprised the program itself accompanied by a string representation of the same program. Dewar's original program was of the same structure. There are notable similarities between this fundamental design principle and von Neumann's design for a self-reproducing automaton, discussed at length in chapter 5 of *Rise of the Self-Replicators*. Furthermore, the same basic principle is employed by nature in the process of reproducing a biological cell—despite the fact that Dewar had not been influenced by biological analogies when designing his quine. Hofstadter (1979, pp. 495–548) discussed the connections between quines and cellular reproduction at length in *Gödel, Escher, Bach*.

My main reason for mentioning quines here is to highlight one other piece of early work in this area that is not often included in histories focused on the field of Artificial Life but that particularly deserves a mention in the current context; this is the MSc thesis of Jürgen Kraus (1980) at the University of Dortmund.[10] Kraus described and implemented various schemes for quines in two high-level languages (SIMULA and PASCAL) and also for self-reproducing programs in a low-level language (SIEMENS assembly language). The latter were of simpler design than Risak discussed in his 1972 paper and more akin to the handwritten self-replicators that would be used to inoculate Tierra and similar systems in later years. At the end of his thesis, Kraus also outlined proposals for models to investigate competition among self-reproducing programs in a shared environment and the addition of mutation to allow for the programs' evolution.

Although he did not actually implement these additional ideas, Kraus was nevertheless one of the first computer scientists to envisage evolution in a population of self-reproducing computer programs (i.e., employing mutation in addition to the self-reproduction of programs seen in Darwin and Core War). Kraus's work was published 20 years after Stahl had implemented these features in 1960 but still a decade earlier than Rasmussen et al.'s Venus and Ray's Tierra systems, which received widespread attention within the Artificial Life community.

As mentioned in *Rise of the Self-Replicators*, for work from the mid-1960s onward, detailed histories of other research into self-reproducing and evolving digital organisms, collectives, and ecosystems—including self-reproducing programs, string systems, cellular automata, and simulated

9 The term *quine* was coined by Douglas Hofstadter (1979) in his book *Gödel, Escher, Bach*, a decade after the original conception of this kind of program.

10 An English translation of Kraus's 1980 thesis, with forewords by editors and translators Daniel Bilar and Eric Filiol (2009), was published in the *Journal of Computer Virology and Hacking Techniques*.

agents—can be found in various sources (e.g., Banzhaf & Yamamoto, 2015; Dorin et al., 2008; Reggia et al., 1998; Sipper, 1998; Taylor, 1999).

5 Closing Remarks

The three most significant works I have inserted into our history of thought about self-reproducing and evolving machines in the preceding sections, by Etzler (1833), Karinthy (1916/1978), and Stahl (2013a, 2013b), are contributions of three different flavors: a utopian inventor's plans for the physical self-reproduction of mechanical devices; a fiction writer's vision of a world inhabited by superintelligent machines; and a computer programmer's creation of an artificial universe in which digital organisms could reproduce, mutate, and evolve. Each work brings its own contribution to the history.

Ideas in science fiction often precede their development by scientists and engineers (and that is one reason why I have included discussion of sci-fi works in this history). Although this was certainly true for many of the gadgets Alfvén envisaged in *The Tale of the Big Computer* (Johannesson, 1966/1968), Etzler's inventions and proof-of-concept experiments as a first step to achieving his dreams of a work-free society powered by self-reproducing machines—though largely unsuccessful and a long way short of fully realizing his vision—are an example of engineering work preceding science fiction on the topic. Writing at the climax of the British Industrial Revolution, Etzler's emphasis on renewable energy to power the exponentially expanding activities of his machines was certainly ahead of its time.

In section 7.1.4 of *Rise of the Self-Replicators*, we discussed the variety of schemes for achieving self-reproduction proposed in the works we reviewed. To extend that discussion to the works covered in this afterword, a popular scheme has been self-reproduction achieved by a collection of robots manufacturing parts of a whole, where the parts are later assembled into a full copy of the original robots. It seems reasonable to conclude that this is the kind of scheme that Etzler envisaged. It is also the scheme discussed more explicitly by Karinthy, Alfvén, and others.

A variation of the theme of collective self-reproduction appears in various works, including Hamilton's 1926 "The Metal Giants," Hasse's 1936 "He Who Shrank," and Hugi's 1941 "The Mechanical Mice." This variety involves a central superintelligent machine that directs a collection of lesser robots to perform various tasks, including assisting in its reproduction. These stories often involve the idea that the central machine can *design* its own offspring rather than simply replicating its own design or relying on mutations to power the evolution of its kind. This concept of self-designing machines was also present in some of the works reported in *Rise of the Self-Replicators*, as highlighted in section 7.1.1 of the book.

Turning to Stahl's (2013a, 2013b) contribution, his work significantly extends—by 30 years—the history of building ecosystems of self-reproducing computer programs with the capacity for mutation and evolution, even though he conducted only minimal experimentation with the system. It is also 10 years prior to Conrad and Pattee's (1970) early studies of the evolution of artificial ecosystems, which were not based on self-reproducing computer programs. Stahl's work is—as far as I am aware—only the second example of a computational system designed to accommodate the open-ended evolution of self-reproducing structures, after Nils Aall Barricelli's contributions in the 1950s (e.g., Barricelli, 1954, 1957), discussed at length in *Rise of the Self-Replicators*. Barricelli's system was based on a one-dimensional cellular automaton, making Stahl the first to use an assembly language to instantiate digital organisms.

Writing a history of thought about self-reproducing and evolving machines, like writing any other history, is a Sisyphean task; there is always more to be discovered and more to be said. Nevertheless, each addition to the history provides us with a richer picture of where ideas originated and how they developed over years, decades, and centuries. Although this afterword, in combination with the original book, sets out the current state of my understanding of the subject, I cannot, of course, say for certain that no other relevant sources are awaiting discovery. If any such sources come to light, I look forward to the delight of reading them and of reporting them back to the Artificial Life community.

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I am very grateful to Fred Stahl for an email conversation we had in December 2020 about his work on Artificial Life in 1960, and for his comments on a draft of this article in late 2023. Aged in his early 80s, Fred was nevertheless still enthusiastic about discussing his work and other topics covered in the article. Thanks also to Hamish Dewar for the email conversation we had in January 2021 about the self-reproducing program (quine) he wrote in the late 1960s.

I originally became aware of the work of Etzler and Karinthy, and some of the pulp sci-fi stories discussed herein, by reading an article on SciFi StackExchange: https://scifi.stackexchange.com/questions/258722/earliest-example-of-self-reproducing-automata. In particular, I thank users hypnosifl and M. A. Golding for their valuable contributions to the discussion thread. I also conducted an extensive search of the compendium *Science-Fiction, the Early Years* (Bleiler, 1990) using keywords such as *evolve*, *evolution*, *evolving*, *Darwin*, *Darwinian*, *reproduce*, *reproduction*, *replicate*, *replication*, and *superintelligent*. Apart from the two stories of the creation of life in a test tube and its subsequent evolution, mentioned in footnote 2, this search did not uncover any material not already mentioned in *Rise of the Self-Replicators* or in this afterword.

Many thanks to James McIntyre for reading over a draft version of the section on Etzler. Thanks also to John Clute and David Langford for their assistance in my search for the true identity of "Dudbroke," author of *The Prots* (even though the search did not lead to a conclusive result!). And finally, a big thank-you to Alan Dorin for his invaluable contributions and support in writing our original version of this history in *Rise of the Self-Replicators*.

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