10 Developing Insights into the Design of the Simplest Self-Replicator and Its Complexity: Part 2—Evaluating the Complexity of a Concrete Implementation of an Artificial SSR

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Abstract

This is the second in a three-part series investigating the internals of the simplest possible self-replicator (SSR). It builds on the construction of a hypothetical self-replicator devised in Part 1 and considers various significant aspects about the design and construction of an artificial, concrete SSR: the material basis of its construction, the effects of the variable geometry of the SSR during its growth through the cloning and division phases, and the three closure rules that must be satisfied by the SSR—energy closure, material closure, and information closure.

The highest technical challenges that need to be faced by the design and construction of the artificial SSR are considered. The emerging complexity of the artificial SSR is depicted using a metaphorical comparison of the SSR with a city fully populated by automated machinery that systematically constructs a new city that is identical to the old city without external help but only using the construction

materials that enter through the city gateways. The current level of technology is evaluated to determine if it is sufficient for the successful completion of the design and construction of an artificial autonomous SSR project using either a nano-biochemical basis or or a macro-material basis.

Part 1 of this series analyzed the basic necessary design elements of the simplest self-replicator (SSR), including necessary components, functions, processes, and information. Having established the minimum requirements for the design, this part will discuss the physical implementation of the SSR.

1 The Three Closure Requirements as the Basis of an Autonomous SSR

The SSR must be fully autonomous. This means that it can only obtain raw materials and raw parts from its environment and benefit from (or struggle because of) the environmental conditions specific to its location.

Full autonomy specifically requires the SSR to exhibit the following characteristics (Freitas Jr. & Merkle, 2004):

1. The SSR must fabricate all its energy from input materials, and the generated energy must be sufficient for the SSR to produce an exact replica of itself. This condition is called the *energy closure*.
2. The SSR must use only materials admitted through its input gateways, and these materials must be sufficient for the SSR to grow and generate its daughter. This condition is called the *material closure*.
3. The SSR must use only information that is initially present or stored in the mature SSR, and this information must be sufficient to produce an exact replica of the SSR. This condition is called the *information closure*.

2 The Core Approach to Cloning

This section will try to answer the following important question for the design of the artificial SSR: What is the core mechanism that the artificial SSR will use to accurately clone all of its elements?

Below are two possible answers, and it is likely that most any other imagined answers would be similar or equivalent to one of the two answers below:

1. Design and use a *universal physical copy machine* (similar to a key copy machine but much more sophisticated) that analyzes each part or assembly and produces a copy, with the goal of simplifying the design and avoiding having to maintain such detailed catalogs of information.

2. Use an exhaustive descriptive, operational and constructional SSR information database directing an integrated set of specialized software and computer-controlled automatons, in other words, have sufficient data stored about the makeup of the SSR itself to generate a new copy from that data.

2.1 Why the "universal physical copy machine" approach is not adequate

This approach assumes that the SSR contains a sophisticated machine that can examine and accurately copy all other pieces and machinery comprising the mature SSR. This implies that this universal physical copy machine can even copy itself or, more realistically, make a copy of a copy of itself. In other words, the SSR contains two universal physical copy machines. One, Machine A, is performing the actual copying of all SSR machinery and the other universal physical copy machine, Machine B. So the second copy machine, Machine B, is only used as a model for the first Machine A. The goal for this solution is to use these copy machines A and B to alleviate the need to store as much information about the SSR itself, to have as much software, and to contain as much computer-controlled machinery as in the second approach.

This first solution leads to the following conclusions:

1. It will require another machinery $M^{\text{disassembler}}$, to disassemble Machine B in all its constituent parts: $b_1, b_2, b_3, \ldots, b_N$ so that Machine A can copy each constituent part.

2. Then Machine A will copy all parts $b_1, b_2, b_3, \ldots, b_N$ twice (to create all pieces needed for a clone of Machine A: Copy_A and a clone of Machine B: Copy_B) $ca_1, ca_2, ca_3, \ldots, ca_N$ (for Copy_A machine) and $cb_1, cb_2, cb_3, \ldots, cb_N$ (for Copy_B machine).

3. There will be a need for another machinery $M^{\text{assembler}}$ that will know how to take all the parts $ca_1, ca_2, ca_3, \ldots, ca_N$ and assemble them together into the Copy_A machine and parts $cb_1, cb_2, cb_3, \ldots, cb_N$ and assemble them together into the Copy_B machine.

In order to properly construct $M^{\text{assembler}}$, a vast amount of well-structured information of this nature must be first programmed:

- A catalog of all parts $b_1, b_2, b_3, \ldots, b_N$ and for each such part, a unique identifier and possibly physical and geometrical characteristics (dimensions) of the part

- A store room location (x, y, z) from where the $M^{\text{assembler}}$ machine will pick each one of the parts $ca_1, ca_2, ca_3, \ldots, ca_N$ during the assembly steps to construct the Copy_A machine

- A *catalog of assembly instructions* that contains some geometrical x, y, z instructions and the type of assemblage step (e.g., screwing, inserting, welding, etc.). For example, these assembly instructions may describe processes such as the following:

  - how to put together part ca_2 to the assembly made of parts: (ca_1);
  - how to add part ca_3 to the assembly made of parts (ca_1, ca_2);
  - how to add part ca_4 to assembly made of parts (ca_1, ca_2, ca_3).

  Such descriptions would continue for all parts that need to be included in the assembly.

- A manipulator machine (robot that can follow computerized instructions) to be controlled by the $M^{assembler}$ machine in assembling the $Copy_A$ machine

Although the original impetus for Solution 1 is to avoid mountains of information and armies of automatons and machinery, this solution requires those ingredients. There is no magic copy machine that can do its work without structured collections of information and many helper automatons (machinery) that, in turn, must be information-, software-, and computer-controlled. The conclusion is that there is no "magic universal physical copy machine" solution that is significantly distinguishable from the Solution 2.

Another problem with Solution 1 is that certain components of Machine B may not be fabricated by plain (mechanical) assemblage of parts but rather by using more demanding assemblage processes, such as welding or electro-chemical processes. These processes have no precise means of disassembly, which would prevent the universal physical copy machine from being able to reproduce them.

2.2 Exhaustive information, integrated systems driving information-controlled automatons

Since the universal physical copy machine approach does not work, the only other replication method designs the SSR as a collection of integrated sub-systems, controlling a large variety of automatons using a significant collection of integrated information catalogs (databases).

A number of information catalogs have already been mentioned while identifying specific SSR functions. Any informational SSR function has both an associated catalog and also a set of access sub-functions that provide a set of access operations to the information catalog that can be used by other SSR functions to execute specific action sequences.

3 The Material Basis of the SSR

When approaching the task of the design and implementation of an artificial SSR, a capital question surfaces rather quickly: What should be the material basis for the artificial SSR? There are two distinct possibilities: Either use a biological basis for the SSR on a micro/nano scale or use more common macro scale materials and technology.

3.1 Using a Biological Basis for the SSR

Using a biological basis for the SSR means that the SSR must be constructed using organic materials. These materials would be the same or similar to those used by the cells, tissues, and organs of the living world. There are several advantages to this approach. First, the proof in the feasibility of this approach is the presence of the varied organisms and microorganisms in nature. A key question is whether this approach is accessible given current engineering technologies. Second, even though energy generation is one of the biggest challenges for SSR replication, there are known levels of energy consumption based on biological systems. Lastly, biological systems tend to be in aqueous medium, which may facilitate solutions for the variable geometry problem.

The biological approach is not without its setbacks. First, since this approach operates at extremely small scales, it taxes the limits of current investigative tools and observational methods. The most advanced microbiology manipulation and fabrication tools/approaches are still rather primitive and very limited when considering the tasks that need to be accomplished: fabrication, assemblage, manipulation at nano scales, computing machinery fabrication, software execution, information storage, and communication. Secondly, there are many aspects of cell biology that are still beyond current understandings of the cell's function. Examples of the challenges that we cannot solve with current technology include

- building computers on a biological material basis/scale (or understanding how the cell proteins and other organic cell elements can be used for computation in a general way)
- building bio-chemical manufacturing machines at a biological scale
- building information storage using biochemical materials
- having software running on biological type computers
- communicating information on a biological material basis and at a biological scale

Clearly, the conclusion is that, with the current level of technology, it is impossible to create a design and an implementation plan for an artificial SSR using a biochemical and a biological material basis at a molecular scale. Other alternatives must be considered for a better chance of successfully building an artificial SSR.

3.2 Using a Macro Scale Basis for the SSR

The other alternative for consideration is the macro scale approach, using materials and technology that are in common use for product fabrication. This approach must consider the minimum dimensional scales for which there are available manufacturing technologies for most of the parts, components, and machinery that make up the SSR.

The materials used to construct the SSR enclosure, SSR scaffolding, and SSR interior should be common engineering materials used by current fabrication technologies: metals, alloys, plastics, ceramics, silicon or other special materials. The scale of these artifacts to be fabricated as elements of the artificial SSR must be selected with care as there are two opposing considerations which must be balanced and compromised.

The first consideration is that the smallest possible scale should be used in the design and implementation of the artificial SSR parts in order to minimize the energy consumed by the SSR during a replication cycle and minimize the size, volume and mass of the artificial SSR in order to minimize the number of materials ingested into the artificial SSR and used for fabrication of the clone within the SSR.

However, this must be balanced with the limitations of known engineering technologies and machinery to fabricate, manipulate and assemble all the parts of the SSR machinery. This means, for an illustrative example, that if the minimum size of semiconductor fabrication equipment that is being manufactured today is 0.5 meters, then the designed size of the mature artificial SSR cannot be smaller than 1 meter. Therefore, a more realistic artificial SSR design would have dimensions in the range of at least 10–100 meters.

4 The Type and Nature of SSR Components

The conclusion in Part 1 was that the SSR must be designed and implemented as a collection of integrated, computer-controlled and software-controlled automatons. The artificial SSR must, by necessity, contain these types of elements:

- Computing machinery, which implies that the following type of elements must be present inside the artificial SSR:
  - Printed circuit boards (PCB)
  - Microprocessors

  - Highly integrated circuits (Application Specific Integrated Circuits = ASICs)—specialized, high density integrated circuits for specific computing/application tasks, such as networking, numerical processing, image processing, etc.
  - Semiconductor memories (solid state memories)
  - Magnetic memory (hard drives)
  - Electric power supplies
  - Computer connectors and wiring

- Networking Communication Devices:
  - Routers (wired/wireless)
  - Switches
  - Modems
- Software
- Robots
- Energy generation and distribution machinery
  - Generators
  - Transformers
  - Converters
  - Wiring
- Batteries
- Fabrication machinery
- Metal machining machinery

5 Derived Design Requirements

This section is a list of design and implementation requirements for the artificial SSR that emerged from the previous analysis and from the inferences presented so far. These requirements were only implied during the discussion so far but are now made explicit and are described in some detail.

5.1 Each SSR Machine is Power-Driven

If each SSR machine is power-driven, then certain significant consequences arise in designing an artificial SSR:

- The SSR must have a power distribution network (e.g., an electrical distribution network) that must reach each of the SSR's machinery. The design of the layout and geometry of the power network must consider the variable geometry of the SSR enclosure, scaffolding, and interior space and structure. Particular consideration must be made for the zones affected by growth and shape changes.
- Each SSR machine must be designed to use and consume power (electricity) at a level adequate for its nature and the actions it performs.
- The machinery is computer driven, which means that either there is a parallel SSR power network for an energy level (e.g., voltage) adequate for computing devices, or each machine must have some adequate power converters (e.g., electrical power supplies or batteries).
- The SSR machines that provide mechanical work or movement must be provided with motors (rotational and/or linear) adequate for their nature.
- Mobile machinery (e.g., transporters, moving robots) must be designed such that their mobility is not constrained while they are connected to the SSR power network(s). Designing all mobile machinery with rechargeable batteries may solve or significantly simplify the connectivity constraints but will require additional provisions for battery fabrication processes and fabrication and provision of battery charging stations.
- The design of each machine must provide specification for the average power consumption on all power networks (normal power level and computer power level) to which the machine is connected.

5.2 Each SSR Machine is Computer-Driven and Software-Driven

If each SSR machine is computer-driven and software-driven, then there are several consequences to consider in designing an artificial SSR:

- Most SSR machines must host at least one internal computer with the possible exception of some simpler (e.g., electro-mechanical) machines that can be remotely controlled.

- The SSR must have highly technical machinery and processes to fabricate computers and their respective parts.
- Each SSR machine that hosts computing devices must be networked—by wire or wirelessly—to other machines and control centers within the SSR.
- The SSR must have adequate machinery to not only fabricate computers but to install them into other SSR machines, plug them into the other machine's power network, and connect them to the SSR's communication network.
- The SSR must have machinery that is able to download and copy software into any computer installed into an SSR machine, to start (boot) that software on the machine, and to monitor its availability and behavior.
- The SSR must have the capability to test each piece of its machinery, to detect malfunctions in computer and software installations as well as in the machine hardware, to detect malfunctions in the computer and software execution and to have adequate procedures to diagnose and repair the identified problems. Diagnosis and repair may be based on the availability of fabricated spare parts.
- The software that drives each particular piece of machinery must be designed and written with a full understanding of the physical and cinematic capabilities and constraints of that piece of machinery. It must take into account all possible uses of the machine and all its components' behaviors and interactions with external objects and events as well as be able to handle them correctly.
- The software that drives fabrication and assemblage machinery and materials and fabrication processes needs to be based on a thorough design of the machines that will be built, their cinematic capabilities, and their specified power and energy consumption.
- The software written for various SSR functions must carefully and accurately coordinate and synchronize the activities of multiple SSR machines (e.g., fabrication machines, material process machines, manipulation and transport robots/arms, assemblage and construction machines) by providing a continuous monitoring of the 3D spaces occupied by each machine and its mobile parts to avoid collisions and to ensure cooperative progress with both lower level and higher level tasks of the growing SSR.

5.3 Each Piece of SSR Machinery Is Capable of Information Communication

If each piece of the SSR's machinery must have the ability to communicate information, then several features must be included in its design:

- The artificial SSR is a collection of automated machines and robots. Their cooperation and coordination for achieving tasks from the simplest (e.g., fabricating a part, or manipulating a part in a sequence of steps for an assemblage operation) to the most complex ones (e.g., the fabrication and assemblage of computing hardware and software installation for a new piece of fabrication machinery) requires extensive, continuous, multipoint, and multi-level communication of information between machines, control functions, and software components.

- The SSR must have a comprehensive physical layer communication network for information transport (wire-based and/or wireless) with access points located on each, if not most, SSR machines/robots and sometimes in between the subsystems of the same SSR machine.

- The SSR might need to have adequate networking devices (e.g., routers, switches, modems, and codecs) to implement needed communication patterns and topologies.

- The SSR machine and software components engaged in communication will need adequate networking/communication protocols with appropriate characteristics for carrying the needed communication bandwidth, handling errors and retransmissions, reliable routing, and end point addressing.

- The SSR should have the ability to deploy software on newly constructed machines and network nodes, and to bring up the network and verify it as part of starting up the daughter SSR system (including its underlying communication network) as a preparatory step in the SSR division phase.

6 The Most Significant Challenges for the Design and Implementation of an Artificial SSR

6.1 The energy generation and the energy closure challenge

The energy generation and energy closure challenge presents multiple hurdles which must be resolved. Primarily, the SSR design must select an adequate basis for energy generation. This depends on what natural materials are available in the SSR environment that can be used for energy generation. Some of the candidate material basis for energy generation that might be considered for the design and implementation of an artificial SSR might include biochemical or organic (e.g., vegetation used for energy generation), coal, oil/petroleum, natural gas, methanol, hydrogen, solar, wind, and/or nuclear.

The *energy closure challenge* means that the amount of energy generated by the SSR from the primary energy producing materials extracted from the SSR environment must be sufficient to power all machinery (e.g., fabrication, assemblage, construction, transport, manipulators, robots, computers, and networking gear) that equip the SSR.

Other challenges associated with energy closure include the following:

- The SSR must be designed with the ability to slow down or even completely shut down during the periods when the input of energy producing materials is reduced or null.
- The SSR's ability to provide the means to store energy (with batteries, accumulators or stocking energy-producing materials) may smooth out or eliminate the need for transition to "hibernation" or shutdown states.
- Designing SSR machines with local sources of energy (e.g., rechargeable batteries, accumulators, fuel reservoirs, or fuel cells) may provide true, unconstrained mobility and may significantly simplify the SSR design and implementation difficulties related to keeping all mobile machines hooked to flexible power wiring or network wiring.
- Burning fuels or chemically generating energy leads to additional concerns in designing and implementing an artificial SSR. Particular concerns include preserving the SSR's internal environmental parameters (e.g., temperature and humidity), avoiding hazardous materials, and providing storage transportation containers for liquid or gaseous materials.

6.2 The material closure challenge

The material closure challenge for designing and implementing the artificial SSR can be summarized as follows: all fabrication materials that are needed for fabricating the parts of the SSR machinery must be available in the SSR environment or must be extracted from raw materials available in the SSR environment.

While this may not appear to be a daunting task, upon closer consideration, the artificial SSR will need fabrication machinery for metal machining, computers with semiconductor microprocessors and memories, plastics, and ceramics. There is potentially an extremely long list of materials needed for SSR fabrication. For example, looking at a short subset of materials needed for the macro scale artificial SSR provides insight into the size of the challenge:

- Iron
- Steel (of various varieties)
- Copper

- Aluminum
- Metal alloys (of different varieties)
- Silver
- Gold
- Ceramics
- Plastics
- Silicon
- Polytetrafluoroethylene (Teflon) for Printed Circuit Boards (PCBs)
- Tin
- Nickel
- Germanium

Even given the partial list above, it appears that there is a very small probability that the SSR's local environment will feature such a large diversity of immediately available materials or components from which the materials in the list could somehow be extracted. This makes the material closure requirement appear *unsolvable*, and thus any project to design and implement an artificial macro-scale replicator may be condemned to failure.

Another way to formulate the material closure challenge is that a successful selection of materials used for energy generation and fabrication of internal parts, components, and machinery must be based on a thorough knowledge of the environment in which the designed SSR is projected to exist, including the nature of raw materials and parts in such environment, and realistic material extraction paths and processes. In other words, the success requires a perfect design of *both* the SSR and its environment.

6.3 The Fabrication Challenge

The fabrication challenge is the requirement that the artificial SSR must be able to fabricate and assemble any type of parts, components and machines that are part of the mature SSR, which implies that all fabrication and assemblage machines should be able to fabricate exact copies of themselves.

While the material closure challenge focuses on the difficulty of having a wide spectrum of fabrication materials readily available, the fabrication challenge raises several other concerns.

- Since the artificial SSR will have much machinery made with metals (e.g., fabrication machinery, construction and assemblage machines, robots, manipulator arms, networking gear, wires, power supplies, conduits, and scaffolding), the SSR must have a diversity of metal machining machinery.
- The SSR must be able to fabricate the necessary machinery and enclosures for energy generation, as specified above.
- The SSR must be able to fabricate machinery and enclosures to control and host a very wide set of processes (e.g., material extraction, energy generation, possible chemical reaction processes, electrolytic processes, and PCB etching chemical processes).
- The SSR must be able to fabricate computers and computer parts including microprocessors, integrated circuits, application specific integrated circuits (ASICs), signal processing integrated circuits, controller integrated circuits, printed circuit boards (PCBs), power supplies, cabling, semiconductor memories, magnetic memories, and media (hard drives, solid state drives). This also implies that the SSR must feature highly demanding "clean room" spaces that robotically manipulate materials and parts as well as perform semiconductor fabrication.

6.4 The Information Closure Challenge and the Hardware/Software Completeness Challenge

The SSR's information closure is the requirement that the information contained in the SSR is sufficient to drive its successful replication without any additional external information. Completing the hardware and software requirements further extends the information closure requirement by demanding that the computing hardware and software present in the SSR together with the information resident in the SSR are sufficient to drive, control, and successfully complete the cloning and division phases of SSR replication. The SSR's hardware and software must provide full automation of the control, fabrication, assemblage, and the handling of special situations like error detection, error repair, and recovery after error.

The *design of the information* resident in the SSR must be appropriate for its self-replication. Its characteristics must be complete and adequate for the task. It must cover all relevant aspects that intervene during replication (e.g., materials, parts, processes, procedures, plans, spatial structures, error and recovery handling, etc.). Completeness means also that the information designed and stored in the SSR is correctly correlated with the SSR environment. That means, for example, that the SSR design should be based on an accurate and exhaustive list of raw materials and raw parts that exist in the SSR environment together with the material identification procedures and material processing/extraction procedures for those materials. Additionally, it must be adequate for the task in that it must cover all descriptive details of all entries in the information catalogs, with all relevant properties for these entries, including the correct representation of various relationships between the entries in the information catalogs.

The *computing hardware and software completeness requirement* has several implications. The designed computing hardware and software for each machine must be complete, sufficient, and adequate to control, drive, and monitor that particular machine. It must answer commands from the SSR control centers and properly communicate information, status, and control commands with other machines as needed to accomplish the higher level functions of the SSR. Additionally, the hardware and software that are used by various SSR functions and control centers are also complete, sufficient, and adequate in that they cover all possible use cases including errors and incidents.

6.5 The Highest Challenge: The SSR Design Challenge

The SSR design challenge simply means that the SSR's design, including the design of all its subsystems (reviewed in the previous sections), are adequate for accomplishing successful self-replication of the fully autonomous SSR with preservation and without degradation of the self-replication capability that is passed to all generations of daughter SSRs.

There are several specific aspects of the design challenge enumerated below:

- The design of the SSR must be fully coordinated with the design of the environment in which the SSR will be placed. This means in particular that the SSR's design needs to be fully informed about the nature, characteristics, and environmental conditions (e.g., temperature, pressure, humidity, and aggregation status) of the medium where it will exist, including the nature of raw materials and raw parts that are present in this medium.

- The analysis conducted so far reveals that the design and construction of a fully autonomous self-replicating SSR are *extremely demanding*. The success of such a design and construction appear to be heavily determined by the appropriate choices, listed below, and how these choices harmonize with the SSR environment:

    - the material basis of the SSR (nano scale chemical basis or macro material basis)
    - the overall aggregation status of the SSR components: liquid, solid (compact or with embedded spaces), aqueous, colloidal
    - the scale of the mature SSR

- the availability of energy-generation materials and processes in the material basis of choice and at the scale of choice
- the availability of well mastered techniques for the SSR material basis of choice, scale of choice of fundamental engineering techniques including energy-generation and transport, fabrication, assemblage and construction, transport and mobility, manipulation, computation, information communication, and sensing.

7 The Emerging Image of the Artificial SSR

An artificial SSR is very similar to a modern city enclosed in a dome-like structure that communicates with the outside world by well-guarded gates used by robots to bring in construction materials from outside the city. This modern city has two quarters: the "old city" with its fully functional infrastructure in place including buildings, plants, and avenues. The "new city" quarters are initially a small, empty terrain. As the new city is being constructed and its area extends, the dome covering gradually extends to cover both the old, established city and the new, growing city. Both the old city and new city quarters are pulsating with construction activity: automated machines (robots) carry new materials, parts, and components that are used to construct the infrastructure of the new city quarters into an exact replica of the old city and to continuously extend the dome on top of it.

The old city contains the following structures that must be replicated in the new city:

- material mining sub-units
- metallurgic plants
- chemical plants
- power plants
- an electricity distribution network
- a library with information for all city construction plans in electronic form that is made available on the city web and used by the city control centers, its machinery, and robots
- a network of avenues, alleys, and conduits for robotized transportation
- fully automated and robotized manufacturing plants specialized in fabrication of all parts, component assemblies, and machines that are present in the old city

- a fully automated semiconductor manufacturing plant with clean rooms for fabrication of microprocessors, ASICs, memories, and other highly integrated semiconductor circuits and controllers
- a computer manufacturing plant
- a network equipment manufacturing plant
- an extended communication network connecting all plants and robots
- a software manufacturing plant and software distribution and installation of robotized agents
- warehouses and stockrooms to store raw and fabricated materials, parts, components, assemblies, and software on some storage media
- a materials and parts recycling and refuse management plant
- an army of intelligent robots for transportation, manipulation, fabrication, and assemblage
- an army of recycling robots that maintain clean avenues and terrains in the city, collect debris from various plants and reintroduce the recyclable materials and parts into the fabrication process while the unusable parts are taken out of the city gates
- control, command, and monitoring centers that coordinate the supply of materials and the fabrication of an identical copy of the original plants, avenues, factories, and stockrooms
- a highly sophisticated, distributed, multi-layered software system that controls all plants, robots, and communications in a cohesive manner

Each one of the transport carriers, robots, manipulators, and construction machinery is active and does its work without impeding the movement of any other machine. Everything appears to be moving seamlessly and orderly, and the construction of the new city is making visible progress under the growing pylons of the bolting dome.

When the new city quarters are completed and they look like the old city, the machinery and robots of the new city become active, bringing the city to life. Something starts happening as well: machinery and robots from both the old and the new city start remodeling the supporting pylons and the arching dome. What used to be a single, super-arching dome is changing shape into two separate domes one for each of the city quarters.

The final steps require the two teams of robots to coordinate as they complete the separation process of the old city and the new city. The new city has its own dome that has been shaped and separated from the original city. What were once two quarters of the same city is now two completely separate cities starting their own, separate destinies.

8 A Brief Survey of Attempts to Build Artificial Self-Replicators

No successful attempt has been made so far to build a real autonomous artificial SSR from scratch. W. M. Stevens summarizes the situation in the abstract of his PhD thesis:

> Research into autonomous constructing systems capable of constructing duplicates of themselves has focused either on highly abstract logical models, such as cellular automata, or on physical systems that are deliberately simplified so as to make the problem more tractable (Stevens, 2009).

Stevens reviews some of the attempts made at building physical or abstract self-replicating machines:

- **Von Neumann's kinematic model.** The system is comprised of a control unit governing the actions of a constructing unit, capable of producing any automaton according to a description provided to it on a linear tape-like memory structure. The constructing unit picks up the parts it needs from an unlimited pool of parts and assembles them into the desired automaton. The project was far from being finished and remained an abstract model when von Neumann died (Stevens, 2009).

- **Moses' programmable constructor.** Matt Moses developed a physical constructor designed to be capable of constructing a replica of itself under the control of a human operator. The system is made of only eleven different types of tailor-made plastic blocks (Moses, 2001).

- **Self-replicating modular robots.** Zykov, Mytilinaios, Adams, and Lipson built a modular robotic system in which a configuration of four modules can construct a replica configuration when provided with a supply of additional modules in a location known to the robot (Zykov, Mytilinaios, Adams, & Lipson, 2005).

- **The RepRap project and 3D printing**. Bowyer et al. have developed a rapid prototyping system based around a 3D printer that is capable of being programmed to manufacture arbitrary 3D objects. Many of the parts of the printer that are assumed to be self-reproducing cannot be manufactured by the system itself. Those parts happen to be the most complex ones (e.g., the computer controller) (Bowyer, 2007).

- **Drexler's assembler.** In *Engines of Creation*, K. Eric Drexler describes a molecular assembler that is capable of operating at the atomic scale. The molecular machine has a programmable computer, a mobile constructing head and a set of interchangeable reaction tips that will trigger chemical reactions designed to construct any object at molecular scale (Drexler, 1986). This proposal stirred quite a controversy with some scientists who were skeptical of the feasibility of such a project (Smalley, 2001).

- **Craig Venter's synthetic bacterial cell and synthetic biology**. Craig Venter and the scientists at J. Craig Venter Institute in Rockville, MD reported in the May 20, 2010 issue of the journal *Science* that they created a "new species—dubbed Mycoplasma mycoides JCVI-syn1.0—that is similar to one found in nature, except that the chromosome that controls each cell was created from scratch" (Smith, 2010; Gibson et al., 2010). In the same ABC news report, Mark Bedau, professor of Philosophy and Humanities at Reed College in Portland, Oregon, called the new species "a normal bacterium with a prosthetic genome" (Smith, 2010).

- **Synthetic biology** is a new area of biological research and technology that combines science and engineering. It encompasses a variety of different approaches, methodologies, and disciplines with a variety of definitions. The common goal is the design and construction of new biological functions and systems not found in nature (Heinemann & Panke, 2006). There are interesting advances in this field with the development of various techniques in domains like synthetic chemistry, biotechnology, nanotechnology and gene synthesis. However, these are far from constituting a complete, coherent, and effective set of techniques that will allow the construction and synthesis of the large diversity of machinery and functions that were identified in the preceding text as the "portrait" of the artificial SSR.

- **Micro-electro-mechanical systems (MEMS)** is the technology of very small devices; MEMS are also referred to as *micromachines* in Japan or *microsystems technology* (*MST*) in Europe. MEMS are comprised of components between 1 to 100 micrometers in size with devices generally ranging between 20 micrometers (20 millionths of a meter) to a millimeter (i.e., 0.02 to 1.0 mm)(Lyshevski, 2000). The technology made significant advances with several types of MEMS currently being used in modern equipment. Some examples include accelerometers, MEMS gyroscopes, MEMS microphones, pressure sensors (used in car tire pressure sensors), disposable blood pressure sensors, and micropower devices. This is probably one of the most promising types of technology for implementing small-scale, artificial SSRs. However, there are still significant hurdles, some of which include implementation of mobile elements (mini robots) and the common difficulty of fabricating the machinery that fabricates MEMS and microprocessors.

- **NASA Advanced Automation for Space Missions 1980 Project.** This study, titled "A Self-Reproducing Interstellar Probe" (REPRO), is one of the most realistic explorations of the design of an artificial "macro" self-replicator and is briefly analyzed in its own section below (Freitas Jr., 1980).

8.1 NASA Advanced Automation for Space Missions Project

One of the missions of the NASA Advanced Automation for Space Missions Project is described in chapter 1 of its final report:

> Mission IV—Self-Replicating Lunar Factory—an automated unmanned (or nearly so) manufacturing facility consisting of perhaps 100 tons of the proper set of machines, tools, and teleoperated mechanisms to permit both production of useful output and reproduction to make more factories. (Freitas Jr. & Gilbreath, 1982)

Later, in the same chapter, the project of making a self-replicating lunar factory is described in detail:

> The Replicating Systems Concepts Team proposed the design and construction of an automated, multiproduct, remotely controlled or autonomous, and reprogrammable lunar manufacturing facility able to construct duplicates (in addition to productive output) that would be capable of further replication. The team reviewed the extensive theoretical basis for self-reproducing automata and examined the engineering feasibility of replicating systems generally. The mission scenarios presented in chapter 5 include designs that illustrate two distinct approaches—a replication model and a growth model—with representative numerical values for critical subsystem parameters. Possible development and demonstration programs are suggested, the complex issue of closure discussed, and the many applications and implications of replicating systems are considered at length. (Freitas Jr. & Gilbreath, 1982)

Figure 10.1 below is a piece of artwork that was reproduced from the NASA study. The description below the picture describes one of the features as a self-replicating factory: "In the lower left corner, a lunar manufacturing facility rises from the surface of the Moon. Someday, such a factory might replicate itself, or at

Figure 10.1: NASA—The Spirit of Space Missions—created by Rick Guidice

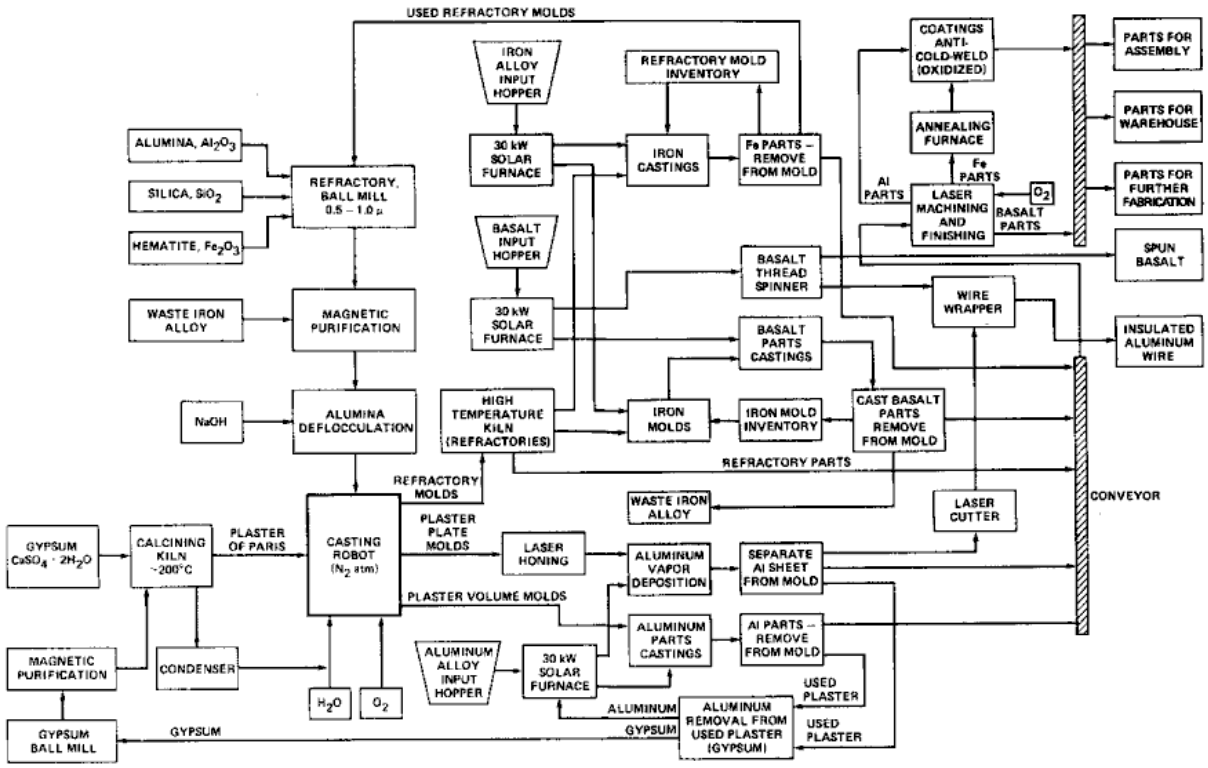

Figure 10.2: LMF Parts Fabrication Sector: Operations (Fig 5.17 in the NASA Study)

least produce most of its own components, so that the number of facilities could grow very rapidly from a single seed" (Freitas Jr. & Gilbreath, 1982).

The project discusses certain details for a self-replicating lunar factory to be feasible. For one, the seed of the lunar factory that would need to be transported from Earth would likely weigh one hundred tons. Additionally, not all of the machinery could be built on the Moon. Certain items, such as computer boards, would need to be brought from Earth since those parts are much too complex to manufacture on the lunar factory. These additional, externally synthesized items are similar to vitamins, which are compounds organisms need to survive but cannot usually synthesize themselves. Scientists estimated that this project would be feasible in the 21st century.

Figure 10.2 illustrates the depth the project reached in considering fabrication facilities on the Moon.

The NASA study represents a thorough, realistic evaluation of the extent that designing a macro-scale (kilometers) self-replicator would entail. It addresses various problems that need to be solved and difficulties that would need to be overcome in order to successfully make a large self-replicator.

8.2 The Self-Reproducing Interstellar Probe (REPRO) Study

In 1980 Robert A. Freitas published a study entitled “A Self-Reproducing Interstellar Probe” (referred to as the REPRO study) in the *Journal of the British Interplanetary Society*. Some of the main goals of the project are summarized below.

- REPRO was designed to be a mammoth self-reproducing spacecraft to be built in orbit around a gas giant such as Jupiter.
- REPRO was a vast and ambitious project, equipped with numerous smaller probes for planetary exploration, but its key purpose was to reproduce. Each REPRO probe would create an automated factory that would build a new probe every 500 years. Probe by probe, star by star, the galaxy would be explored.
- The total fueled mass of REPRO was projected to be 10**10 Kg = 10 **7 tons = 10 million tons for a probe mass of 100,000 tons.
- It would take 500 years for REPRO to create a replica of itself in the environment of a far-away planet.
- The estimated exploration time of the galaxy was 1–10 million years.

9 Simplifying Assumptions for the Design and Construction of an SSR

While the discussion so far has focused on building a fully-autonomous SSR and the difficulties encountered therein, it is possible to reduce the complexity of its design and construction by making some simplifying assumptions. These might include the following:

1. Eliminate the requirement that the SSR produces its own energy. The electrical energy (at an appropriate voltage/amperage) will be supplied to the artificial SSR from the environment.
2. Eliminate the requirement that the SSR has the ability to select, identify and accept through its input gateway appropriate raw materials. All raw materials will be supplied as stock materials to the artificial SSR. An additional, optional simplification could be that all stock materials are labeled appropriately (e.g., with bar codes or RFIDs labels). However, as an illustration, the SSR will still need to use stock copper fed through the input gateways to fabricate copper wires of certain gauges or to use copper in the fabrication of electrical motor parts.

3. Eliminate the requirement that the SSR fabricate the most technically demanding parts, components, and assemblies (e.g., computer boards, microprocessors, semiconductor chips, memories, etc.). These high-technology parts/-components (referred to as “vitamins” in the self-replication literature) will be supplied and carefully labeled from the environment through the input gateways.

4. Eliminate the requirement that the SSR must fabricate any part, component, assembly or machinery from basic materials. The SSR will be supplied with pre-manufactured parts that are used in the composition of all its machinery, scaffolding and enclosure. This simplifying assumption means that now the SSR needs to be designed as a (sophisticated) self-assembler that achieves self-replication by assembling exact copies of itself using an exhaustive pool of all of the parts from the machinery/assemblies it is composed of and are supplied by the elementary parts coming through its input gateways.

5. Eliminate the requirement that the information repositories (information catalogs) that drive the functions of the SSR reside within the SSR. This requirement needs to be replaced with requirements for the SSR to possess reliable, high speed communication capabilities to access the information catalogs (and possibly part of the software) residing somewhere outside the SSR. This assumption may simplify certain elements of the SSR design but will make other requirements, such as communication and availability, more stringent for both the SSR and for the external information resource.

Even if the original requirements for the design and construction of an autonomous, artificial SSR are relaxed and any or a combination of the above simplifying assumptions are used as starting conditions for such a project, there are still significant hurdles that need to be overcome in designing and constructing an artificial SSR.

10 Conclusion

As is evident, the three closure rules which must be satisfied by a true self-replicator—energy closure, material closure, and the information closure—place an extraordinary burden onto the design and implementation of self-replicating objects. The SSR must be able to produce and distribute energy, ingest raw materials to fabricate parts, and contain a complete technical description of itself, its processes, and its assembly instructions. Additionally, the environment for the SSR must also be considered, and perhaps specially designed, in order to make available all of the necessary raw materials for self-replication.

While such replicators are known to exist on a biomolecular scale within nature, current technology does not allow for creating a self-replicator at such small scales. The macro scale implementation is more suited to present technology, though this brings its own problems regarding the scale of energy and materials consumption.

While there have been many attempts to build self-replicators, none of them have satisfied all three closure requirements. The NASA REPRO study was the most exhaustive attempt to design a self-replicator, which estimated the replicator to weigh 100,000 tons (unfueled) and reproduce every 500 years.

While Part 1 and Part 2 of this paper contained an overview of the minimal technological requirements of self-replication and foundational technological implementation considerations, the existence of self-replication in nature comes as quite a surprise. Therefore, Part 3 will cover speculative ideas for what the existence of the self-replication process in nature indicates about the nature of reality.

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