Non-biological 'paralife' and its ongoing transition toward a new form of mechanical life

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Here I describe an overlooked form of non-biological paralife (i.e., near-life) that has been evolving on Earth for millions of years, and is currently in the final stages of transitioning into a new form of life. Any consideration of non-biological life or paralife is complicated by the fact that there is no consensus among biologists for the definition of life. This ambiguity has caused disagreement about whether subcellular reproduction systems like viruses are a form of life, despite having genomes, mutations, heritable phenotypes and system-improving evolution. To resolve this problem, I develop a definition of life that is entirely functional and independent of any of the structural idiosyncrasies of biological life on Earth: an order-generating system controlled by internally-encoded information that perpetuates itself by functioning to counteract its entropic decay. Using this definition, subcellular transposons, plasmids, and viruses are paralife because they match the definition of life in all ways except that they induce their order-generating functioning by a living host rather through their own self-sustaining production system. Using this functional definition of life, I show that utility-products (UPs) like fabricated hand tools are part of induced-reproduction systems that have features equivalent to biological genomes, mutations, heritable phenotypes, and a process of system-improving evolution. The perceived benefit of utility-products causes them to induce their reproduction by a biological life-form (humans). For these reasons, human utility products are functionally just as close to being a form of life as subcellular transposons, plasmids, and viruses, i.e., they are Utility-Product paralife (UP-parlife). I also show that some forms of UP-paralife are currently evolving into mechanical life that is capable of both self-sustaining reproduction and system-improving evolution without outside assistance. This transition requires the development of a high level of factory and/or UP automation and artificial intelligence (AI) that is capable of complex reasoning, imagination and creativity. Finally, I consider the influence of UP-life and UP-paralife on the development of the level of structural complexity in the universe, and I briefly speculate about how these non-biological forms of life and paralife will influence the expansion of scientific knowledge about the universe.

Introduction

Most material objects can be unambiguously classified into one of two discrete categories: animate life and inanimate non-life (Figure 1, top). Only a minority of biological systems, including subcellular plasmids, transposons, and viruses, have an ambiguous classification. The ambiguity derives from the fact that these subcellular forms lack some traits concerning the process of production that are common to all cellular life forms, yet they share with cellular life the same, or very similar, heredity material and genetic code, and they are also capable of adaptive evolution and an induced form of replication. These differences and similarities have led some biologists to categorize the subcellular forms as 'life' while other biologistsof categorize them as 'non-life'. Because of this ambiguity, I will categorize plasmids, transposons, and viruses as an intermediate form of 'paralife' that is near to being alive (Figure 1, bottom-left) and fully justify this classification after I have developed a functional definition of life.

Biologists categorize all non-biological material objects –like rocks, metals, water, and gases– as unambiguously non-life. They also consider

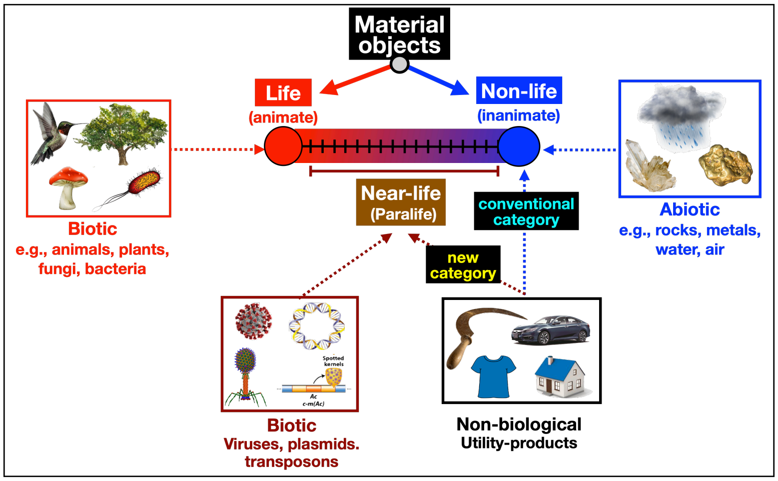

Figure 1. Nearly all material objects can be unambiguously and dichotomously classified as animate life (biological cellular organisms) and inanimate non-life (e.g., rocks, metals, water and gas). Only a small proportion of biological systems (subcellular plasmids, transposons, and viruses) are ambiguous (near-life or 'paralife'), having many properties in common with biological cellular organisms (genomes with the same or similar hereditary material and genetic code, heritable phenotypes and a capacity for neo-Darwinian evolution), but lacking some of their shared core properties (e.g., protein synthesis and homeostasis). Non-biological material objects fabricated by humans (e.g., tools, clothes, housing, machines), which I collectively label as 'utility-products,' (UPs) have historically been classified as non-life. Here I motivate the conclusion that utility-products are part of induced-reproduction systems that are para-alive (UP-paralife) to the same extent as biological paralife, and that some forms of UP-paralife are evolving toward becoming fully alive.

manmade structures like hand tools, clothing, houses, and machines, (which I will collectively label as 'utility-products' abbreviated by 'UPs') as non-life. Here I will show that, counterintuitively, UPs are components of induced-reproduction systems that have the equivalents of biological genomes, mutability, heritable phenotypes, and a capacity for system-improving evolution that makes them para-alive (UP-paralife) to the same extent as sub-cellular plasmids, transposons, and viruses. I will also show that some forms of UP-paralife are currently evolving toward becoming fully alive –plausibly in the near future, i.e., within a few decades.

Compared to the inanimate matter found within stars and their surrounding material objects (spanning the size range from cosmic dust to planets), the matter that collectively constitutes biological organisms on Earth (composed predominantly of water, proteins, nucleic acids, carbohydrates, and lipids) is far more structurally complex (Szathmary and Maynard Smith 1995; Wolf et al. 2018). The genesis of the expanded structural complexity of biotic life forms is predicted by the theory of neo-Darwinian evolution during the gradual transition between a plausible starting point of simple self-replicating molecules during primordial times into more complex living cellular organisms. Additional structural complexity of biological organisms accrued later during the major transitions in life forms (e.g., unicellular to multicellular organisms) that occurred during the evolution of the diverse assemblages of biological organisms found on Earth today (Szathmary and Maynard Smith 1995). Biotic life, and the evolution that it generates, is responsible for one of the major expansions in structural complexity that occurred during the evolution of the universe since its genesis at the big bang (Dalgarno 2006; Lehn 2013).

Functional definitions of life and paralife

The substantial influence of biological life on the evolution of structural complexity raises the question of whether other forms of life and paralife can also evolve that further expand the level of structural complexity within the universe. Answering this question is complicated by the fact that biologists have not reached a consensus for the definition of life despite over 100 proposed definitions (e.g., see Trifonov 2011). One problem with these definitions is that they rely, at least to some degree, on structural attributes or narrowly defined processes that are associated with life on Earth (e.g.,definitions including phrases like 'systems that metabolize', and 'systems made up of one or more cells') –as opposed to a *functional* definition that is applicable in a more universal sense. For example, the definition proposed by NASA in the context of its search for extraterrestrial life is "a *self-sustaining chemical system capable of Darwinian evolution*" (Tirard et al. 2010; https://astrobiology.nasa.gov/research/life-detection/about/). This definition, despite being designed to be general and include life-

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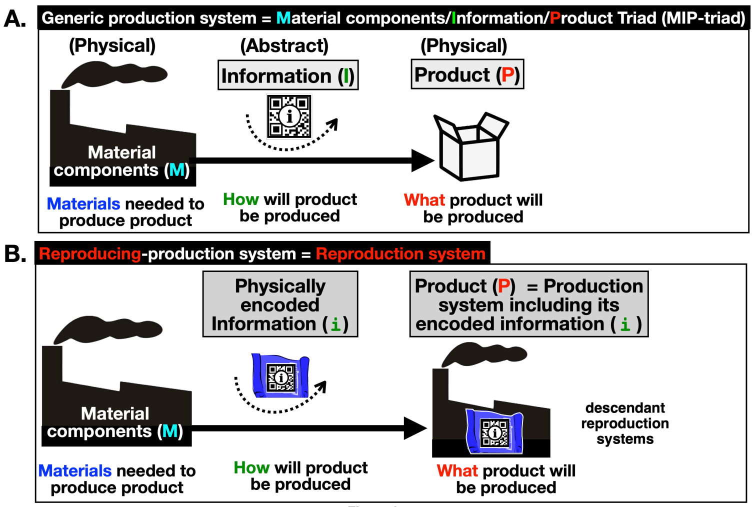

Figure 2

Figure 2. A. Any non-spontaneous production system can be expressed as an MIP-triad of i) material components needed for the production process (M), ii) abstract operation information (I) needed to coordinate the non-spontaneous interactions among the material components, and iii) the physical product(s) produced (P). **B.** A Reproducing production system is one that has a product that includes copies of the system itself, including its physically encoded abstract production information (I). Symbols: i) the factory icon represents the system's material components (M), ii) the box icon represents a generic physical product (P), and iii) the blue-colored blueprint icon enclosing a matrix barcode represents the physically encoded abstract production information (i).

forms beyond those found on Earth, requires the structural attribute of "a chemical system" that precludes any form of non-chemical life (like machine life) and a narrowly defined process of "Darwinian evolution" (presumably referring to Neo-Darwinian evolution based on the modern synthesis [Huxley 1942]) that precludes other forms of evolution that have the same functionality.

To define life from a fully operational perspective, I identify its essential functional features with no reference to how these functionalities are generated. I begin by identifying those functional features that are shared and required by all of the unambiguous forms of life on Earth: that is, the bacteria, archaea, fungi, protists, plants and animals (hereafter referred to as 'Earth-life-forms'). All of these Earth-life-forms function as self-perpetuating and non-spontaneous reproduction systems that are capable of a production processes that is order-generating, self-sustaining, self-replacing and capable of system-improving evolution.

The reproduction process of Earth-life-forms is non-spontaneous because when deprived of an external energy source, all Earth-life-forms become prone to spontaneous loss of the functional organization of their components that is needed for their operation, and eventually irreversibly lose all functionality (death). Although different Earth-life-forms make different products, they share the common features of making copies of themselves (i.e., they reproduce) and a capacity for system-

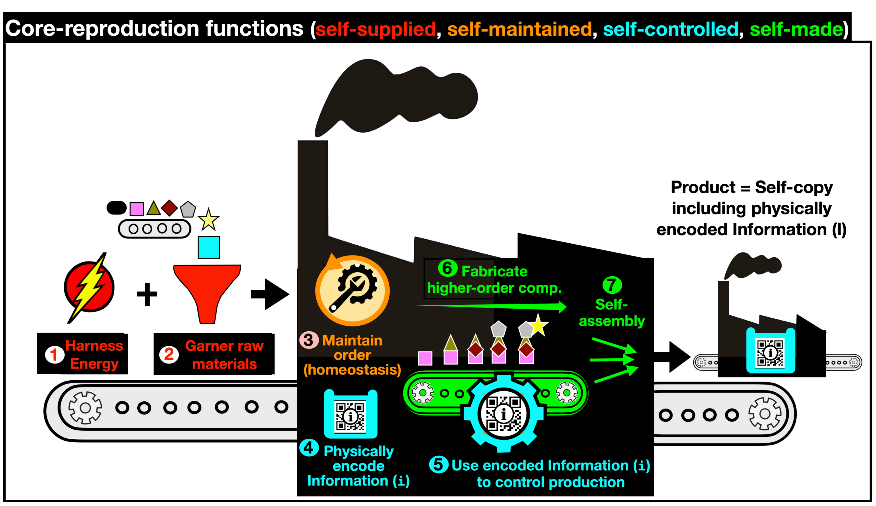

Figure 3. Schematic illustration of the seven core self-sustaining reproduction functions (core-SSR-functs) that collectively enable self-sustaining production with output that includes a copy of the system itself. The system must be: self-supplied (red-labelled functions 1-2), self-maintained (orange-labelled function 3), self-controlled (blue-labelled functions 4-5) and self-made (green-labelled functions 6-7; higher-order components are those not available as raw materials). See text for fuller explanation of the seven functions.

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improving evolution (i.e. adaptation via Neo-Darwinian evolution). Any non-spontaneous production system is intrinsically a triad of three interrelated parts (Figure 2): i) material components needed for the production process (M), ii) abstract operation information (I) needed to coordinate the non-spontaneous interactions among the material components, and iii) the physical product(s) produced (P), i.e., it is an MIP-triad. The abstract information (I) must be physically encoded to make it accessible to control/guide the production process and also to make it reproducible when the system makes copies of itself (Figure 2).

For a production system to be self-perpetuating in a short-term timeframe, despite being energy-requiring and prone to spontaneous disordering, the production process must be order-generating and self-sustaining. To be self-sustaining, the production process must be: i) self-supplied by mechanisms that secure the energy and raw materials needed for its operation, ii) self-maintained by mechanisms that produce the homeostasis needed to counteract intrinsic disordering of the system's components and their interactions during non-spontaneous production operations, iii) self-controlled by mechanisms that: a) physically encode the operation information to make it accessible to guide the non-spontaneous production operations (and also to make it reproducible when during reproduction), and b) decode and use the physically encoded operation information to control the non-spontaneous production process, and lastly iv) self-made by mechanisms that: a) fabricate any product components not available as raw materials, and b) assemble all components to make a completed product (including a copy of itself during reproduction). In sum, the requirements for a reproduction system to be self sustaining include 7 Core Self-Sustaining Reproduction functions (core-SSR-functs; Figure 3):

Core-SSR-functs

1) HARNESS ENERGY to do work and/or drive endergonic reactions
2) GARNER RAW MATERIALS needed for production
3) COUNTERACT DISORDERING PROCESSES to maintain operational homeostasis
4) PHYSICALLY ENCODE PRODUCTION INFORMATION (I) to make it usable & reproducible
5) CONTROL THE PRODUCTION PROCESS via the encoded production information (I)
6) FABRICATE ANY HIGHER-ORDER COMPONENTS absent as raw materials
7) SELF-ASSEMBLE COMPONENTS into a completed product.

Focus next on an intermediate timeframe during which system operation can deteriorate due to senescence (i.e., age-induced reduction in system functioning) and/or death (i.e., complete loss of system functioning). In this timeframe, a system's perpetuation requires a production system that is capable of making new copies of itself (reproducing itself) to regenerate the functional order lost due to senescence and/or death of system units.

Lastly, focus on a longer-term timeframe, during which a system's operation can deteriorate due to changes in the system's environment, and/or in its physically-encoded operation information, that reduce system functioning. In this timeframe, a system's perpetuation requires a system-improving evolution process to counteract these sources of reduced functioning. System-improving evolution is intrinsically required when the environment is prone to changes that reduces system functioning. For example, when the environment includes a Red-Queen process (Van Valen 1977) in which some features of the environment continually evolve to increasingly harm the system, e.g., in a manner like evolving competitors, predators, parasites and pathogens in biological systems. Even in a

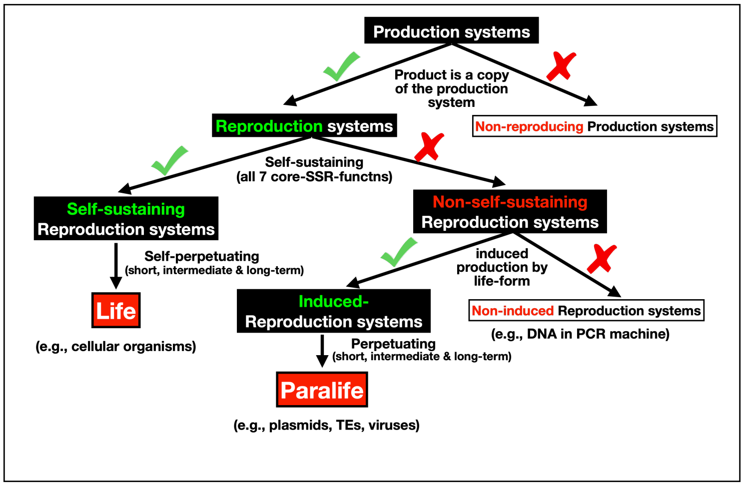

Figure 4. A classification tree for production systems leading to life and paralife.

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constant environment, system-improving evolution is inherently required to counteract entropic erosion of the efficacy of the systems operational control when its physically-encoded operation information experiences spontaneous disordering. Without a correction process for entropic decay of the system's physically-encoded operation information, the system's functioning would continually erode over time and perpetuation would be precluded.

The process of system-improving evolution requires a system to have physically-encoded operation information (e.g., a genome in biological systems) that experiences recurrent modifications (e.g., mutations in biological systems) influencing the system's operations (e.g., heritable phenotypes in biological systems) and cause non-random differential reproduction (natural selection in biological systems) that results in the accumulation through time of modifications that increase reproduction rates (e.g., genetic adaptation in biological systems). Put more succinctly, system-improving evolution requires analogs of biological: genomes, mutations, heritable phenotypes, natural selection, and adaptation.

In sum, life can be functionally defined as a non-spontaneous reproduction system that perpetuates itself by counteracting entropic disorganization through a production process that is order-generating and self-sustaining, an output that includes descendant copies of the system itself, and an evolution process that enables system-improvement. Put more concisely:

Life: an order-generating system controlled by internally-encoded information that perpetuates itself by functioning to counteract its entropic decay.

Increased specificity can be achieved by appending the following clause to this definition: by repair/turnover of its components, system-wide reproduction, and system-improving evolution

More specifically, a non-spontaneous reproduction system that perpetuates itself by counteracting recurrent disorganization must:

i) be order-generating because non-spontaneous production requires recurrent energy input to maintain structural order that is prone to erosion by entropic disordering processes,

ii) be self-sustaining because perpetuating itself due to its own functioning requires that it be self-supplied, self-maintained, self-controlled, and self-made,

iii) have output that includes copies of itself because a system that perpetuates itself requires reproduction to counterbalance loss of functioning when confronted with senescence and/or damage to the point of being fully nonoperational, and

iv) have a system-improving evolution process because a system that perpetuates itself requires a change process to counterbalance reduced functioning when confronted with detrimental features and changes in the system's environment and/or in its physically-encoded operational information.

Nonessential subcellular biological systems like transposons, plasmids and viruses with semi-autonomous replication (i.e., they contain their own hereditary material and replicate independently of the nucleus) nearly correspond to the definition of life with the exception that they induce their reproduction by a life-form (that is capable of all 7 core-SSR-functs) rather than being competent to make their descendant system copies themselves, i.e., they have 'induced-reproduction' rather than self-sustaining reproduction (Figure 4). For this reason I will classify them as paralife (near life or para-alive) and its definition is identical to that of life except the term 'functioning' is replaced with 'inducing functioning':

Paralife: an order-generating system controlled by internally-encoded information that perpetuates itself by inducing functioning to counteract its entropic decay.

In paralife the self-sustaining reproduction of life is replaced with induced-reproduction.

Natural selection, adaptation and the evolution of biological life and paralife

There is a strong consensus that life on Earth was derived from primordial self-replicating molecules, most plausibly composed of heteropolymers of nucleic acids, and possibly also associated amino acids and peptides (e.g., see Ichihashi 2019; Liu

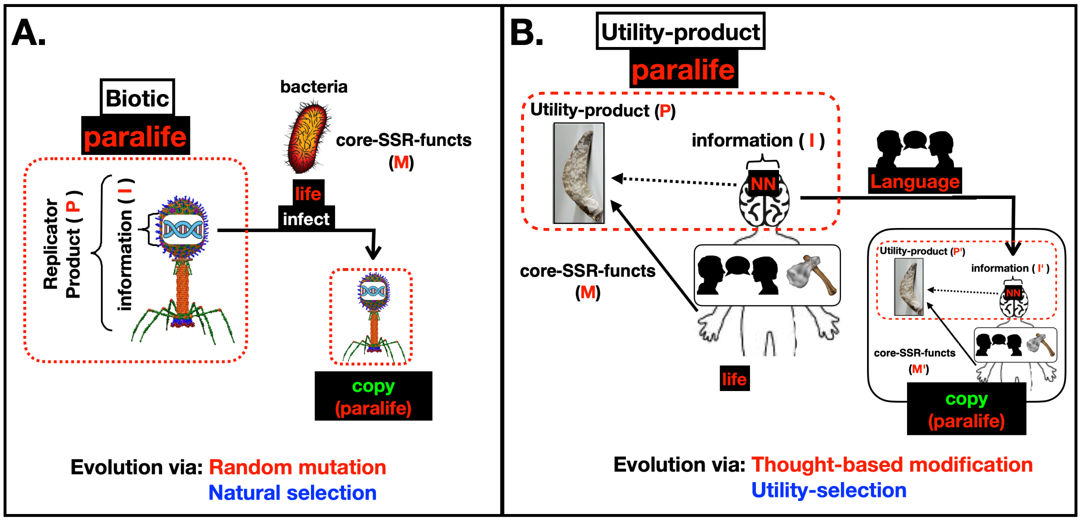

Figure 5. Comparison of an example of biotic paralife (**A.** bacteriophage) and an example of utility-product paralife **(B.** stone sickle). The figure with a brain icon over the head and banner with a tool icon (hatchet) and language icon (facing head silhouettes with a shared speech bubble) depicts a life-form capable of tool-making and language. The red NN acronym stands for neural network engram, and the core-SSR-functs of the life-form are used to fabricate the utility-product.

et al. 2020). When the first self-replicating molecules evolved, they were almost certainly not alive, despite a capacity for adaptation via system-improving evolution, because their simplicity would have precluded their ability to carry out all seven core-SSR-functs needed for self-sustained reproduction. The primordial environment where they first formed would have needed to provide, or somehow circumvent, all or most of the seven core-SSR-functs (like a PCR machine does for an arbitrary DNA sequence). For example, sufficient heat or electromagnetic radiation in a primordial environment could plausibly fulfill core-SSR-functs (i), and core-SSR-functs (ii) could be fulfilled when the subunits of the self-replicating molecules were initially sufficiently abundant in the primeval environment.

Once a suitable molecular structure that was capable of replicating itself was initially and fortuitously formed in a permissive primeval environment, an expanding population of these self-replicators would be expected to change their environment, e.g., because of the depletion of resources and because interfering-parasitic self-replicating molecules (due to mutation) would plausibly evolve and disrupt self-replication (Ichihashi 2019). Such a deteriorating environment would generate natural selection for countervailing adaptations, e.g., longer nucleotide sequences to enable additional functions like new enzymatic activity, liposome encapsulation to compartmentalize reproductive units, and eventually, translation-generated peptides/proteins to expand enzymatic potential. This natural selection for countervailing adaptations would initiate a 'race' between adaptive evolution of the self-replicating molecule(s) and their extinction (i.e., cessation of self-replication) due to the deterioration of an initially permissive environment caused by the expanding population of self-replicating molecules. Assuming extinction does not occur, increasing deterioration of the permissive environmental conditions would require the self-replicating molecules to eventually evolve all seven core-SSR-functs and biological life would have emerged.

As biotic life evolved, it would also create the opportunity for biotic paralife (plasmids, transposons, and viruses). These biological induced-reproduction systems need to infect/inhabit biotic cellular organisms and induce them to carry out those core-SSR-functs that they cannot accomplish themselves.

Utility-products evolving as a non-biotic form of paralife

All forms of biological life and paralife on Earth use heteropolymers of nucleic acid to encode the production information of their self-sustaining or induced reproductive systems, respectively. As described below, the neural networks of animals are similarly able to function as the encoded information (I) components of a different type of paralife that is based on learned information.

Once a form of animal life evolved that was capable of both i) communicating fabrication information to each other, e.g., with words or language, and ii) learning to construct 'utility-products' (UPs), like tools, clothing and any other structures perceived to be useful, an opportunity threshold was achieved for the evolution of a non-biological form of paralife (UP-paralife). In the companion paper (Rice 2022), I focus on the origin of this non-biological paralife in early hominins. Here I only consider the context where at least simple forms of language have already developed.

To illustrate this new form of paralife and its evolution, consider a simple tool like a stone-age sickle (Figure 5B) used by late stone age prehistoric humans to harvest cereal grains (e.g., see Manclossi and Rosen 2019). Intuitively, the stone tool would seem to be an unambiguous example of non-life because it is a reconfigured inanimate stone. However, unlike a stone, the fabricated stone tool is part of an MIP-triad: the tool being the physical product (P), the abstract information to produce the product (I) being physically encoded in a neural network (NN) within a human's brain (as a NN-engram, aka a memory trace), and the material components (M) being the human's core-SSR-functs (Figure 5B, top-left). More specifically, the stone tool is part of a UP-paralife induced-reproduction system because its intrinsic utility stimulates the human to copy the NN-encoded production information (I) to a NN in another human via language (Figure 5B, top-right). The recipient human next uses the newly acquired NN copy of the production information (I') to produce, via its core-SSR-functs (M), one or more copies of the stone tool (P'; Figure 5B, bottom-right). In this way the stone sickle is part an induced-reproduction system that reproduces itself by stimulating a life-form (humans) to use their core-SSR-functs to replicate the induced-reproduction system. This system is functionally equivalent to biological sub-cellular induced-reproduction systems (plasmids, transposons and viruses) that stimulate cellular life-forms to use their core-SSR-functs to replicate them (compare Figure 5A and 5B). Below I provide more detailed description of the logic behind the conclusion that humans' utility-products are para-alive (UP-paralife).

The information needed to make the stone sickle utility-product must have been learned by a prehistoric human –plausibly by reconfiguring an extant stone tool that was originally used for some other purpose. This learned information would have been encoded in the human's brain in the form of a NN-engram, i.e., a configuration of connections within a biological NN (Mayford et al. 2012). Like heteropolymers of nucleic acid, NNs are capable of storing large amounts of complex information (Neilsen, 2015).

The primary route to the stone sickle paralife's reproduction relies on language. Because of the perceived utility of the newly invented tool, the human would be motivated to communicate, via language to other humans (e.g., relatives or unrelated allies), the concept, operation, and production information for the tool (Figure 5B, top-right). Just as DNA polymerase copies the nucleotide sequence information from a biotic organism to its offspring, humans via language would act as a polymerase by copying the tool concept, operation and production information in one human's NN to the NN of another human.

In the replication process, the stone sickle paralife's production information (I) is first translated into a heteropolymer-like sequence of sound-encoded symbols (spoken language) that are perceived via hearing by another human. This recipient human then translates the sound-encoded information (I) into a configuration of connections within a neural network (NN-engram) that resides within their brain. The recipient human next uses the production information stored in their NN (I') to guide/control their core-SSR-functs (M') to make a new copy of the utility-product (P' = stone sickle), and the replication cycle is complete.

A second potential mode of information transfer between humans is observational learning. This mode plausibly operates in animals that make primitive tools but lack language (e.g., chimpanzees), although it has far less potential for the evolution of UP-paralife (as described in the companion paper Rice 2022). For this reason, here I will treat observational learning as a complementary process during the transfer of UP production information via language in modern humans.

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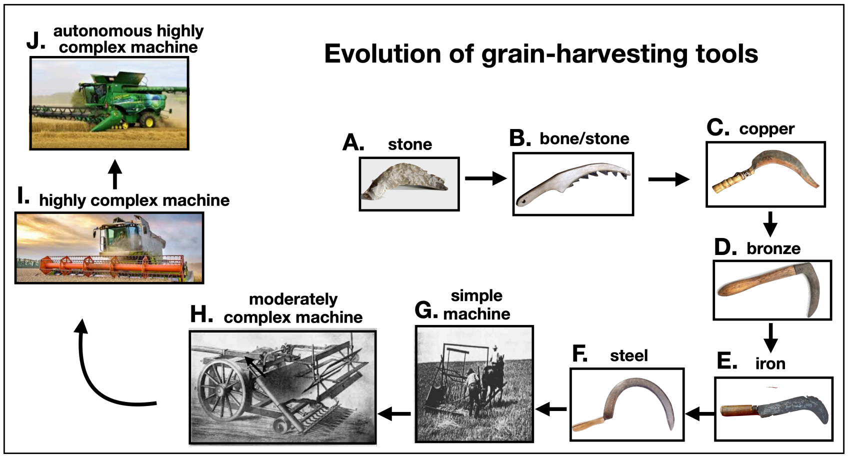

Figure 6. Example of the evolution of a sickle utility-product (paralife) used to harvest cereal grains.

In biotic life and para-life, adaptive evolution is a consequence of i) random or haphazard mutations within genomes that create heritable phenotypic variation among individuals, and ii) natural selection through nonrandom differential reproduction among individuals (Figure 5A). Because utility products like the stone sickle are part of an induced-reproduction system that is para-alive, they can potentially evolve to new forms with increased utility (the analog of genetic adaptation) provided that: i) their physically-encoded production information (I; in the form of NN-engrams that are the analogs of biological genomes) experiences changes (thought-based modifications that are the analogs of biological mutations) and produce new UP variants (the analog of new biological heritable phenotypes), and ii) there is nonrandom differential reproduction of different forms of the utility-product (P) and its production information (I) that favors higher utility forms via utility-selection (the analog of natural selection) (Figure 5B).

Consider again the example of the simple stone sickle (Figure 6A). Reasoning, trial-and-error learning and new learned information from other contexts (like the development of newly learned metallurgy) would allow humans to modify the production information used to make a tool for harvesting cereal grains. Some of these thought-based modifications would produce superior utility-products compared to the extant form, and other modifications would make inferior products. By choosing to replace the old product and its production information with modified versions that had higher perceived functional value (utility-selection), the harvester tool (P) and its associated production information (I) would undergo system-improving evolution through time (Figure 7A-J) to become the highly complex and automated combine harvesters that came into use in the 21st century (Figure 6 I,J).

During the thousands of years of evolution from stone hand-tool to highly automated machine (combine harvester), reading and writing would eventually replace hearing and speaking during the reproduction of the utility-product's induced-reproduction system. Also, written text and computer memory would largely replace brain neural networks for physically encoding the production information (I), i.e., much of information component of the UP-paralife (I) would migrate from human NNs to a form of mechanical storage. In addition, systems of deductive logic like mathematics and computational machines like calculators and computers would augment both the thought-based modifications process and the utility-selection process. Because thought-based modifications are directional –unlike non-directional random/haphazard mutations– and because utility-selection can completely replace an old form of UP-paralife with a newly modified form over a period of time spanning less than one or a few human generations, –unlike the more gradual process of genetic change via natural selection– the speed of system-improving evolution of UP-paralife can be far faster than that of adaptive evolution of biological life and paralife (Figure 6).

The human/machine information spectrum and evolution toward mechanical life

Current-day biotic paralife, (transposons, plasmids, and viruses) is not expected to eventually evolve into more complex biotic life because superior competition from extant, fully-formed biotic life would be expected to competitively block the transition. This evolutionary barrier, however, is absent in the case of UP-paralife. Above, when describing the initial evolution of biotic life, I described a process in which increasingly more complex self-replicators plausibly replaced their progenitors and eventually evolved into self-sustaining reproductive systems because more complex self-replicators (capable of additional and/or more efficient core-SSR-functs) were better competitors in the context of a primeval environment that became increasingly less conducive to self-replication. A similar process is expected to transform simple UP-paralife into complex machine paralife, which in turn would have the potential to evolve into mechanical life.

Again consider the evolution of cereal grain harvesting tools (Figure 6). Because some more complex harvesting tools/machines had higher efficacy, they were perceived by humans to be more useful. As a consequence, utility-selection caused successive steps in the harvesting machines' evolutionary lineage to beget evermore complex descendants. Up until and including the present, the thought-based modifications process in this evolution has been done by humans, most recently by professional engineers. Simple tools like manual drafting rulers and slide-rules, that were used to aid the engineering process, were eventually augmented by computer-based spread sheets, and then more recently by computer-assisted design programs (CADs).

As more learned information accumulated from experience, trial-and-error, and the basic sciences, and as engineering tools became more sophisticated, the machines that engineers could design became far more complex (Figure 6). At the time of this writing, computers are largely used as passive assistants to engineers (i.e., incapable of learning) that 'do what they are told to do' by computer code developed by human programmers. The incorporation of artificial intelligence (AI), especially in the context of machine learning, is expected to lead to a major expansion of the structural complexity of UP-paralife –and plausibly (perhaps inevitably) lead to its eventual transition into mechanical life. When simple utility-products like hand-tools have evolved into more complex machines, I will

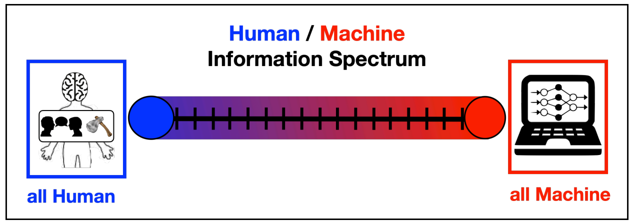

Figure 7. The Human/Machine Information spectrum. The spectrum depicts the relative contribution to information storage, processing and generation (thinking) that controls the design, fabrication, functioning and evolution of a utility-product.

substitute the word machine for utility-product when referring to mechanical non-biotic paralife and life.

The role of machines in controlling, designing and building themselves (reproduction and/or remodeling) can be expressed as a position along a human/machine information spectrum: with a machine pole at one end and a human pole at the other end (Figure 7). The spectrum depicts the relative contribution to information storage, processing and generation (thinking) that controls the machine's design, fabrication, functioning and evolution. To illustrate this spectrum, and how it can evolve in a simple context, I next consider the example of a human playing the game of chess with the assistance of utility-products.

Early-on, sheets of papaya, paper, and parchment (later becoming collections of pieces of these items = books) was a UP used to record one's own chess games and the games of other players. A chess player could use the accumulated written records of chess games within books to learn from his/her accumulated past games and also the games of past master players. Eventually, books were replaced by data stored in computer files and then by simple computer programs that could visually recapitulate past games on a computer screen. Later, computer programs became interactive and could simulate an opponent player –but these simulated-players were poor performers against accomplished chess players. Eventually, in 1997 a supercomputer with specially designed hardware and software for playing chess (IBM's Deep Blue; Hsu 1999) was able to outperform the human world champion (Garry Kasparov). Deep Blue was in turn replaced by a superior performing computer code that could be run on

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the inexpensive-but-fast desktop computers that became available in the early 21st century (e.g., the open-source program StockFish; see Acher and Esnault 2016). Both Stockfish and Deep Blue represent passive, learning-incapable computer programs that 'do what they are told to do' by computer code written by human programmers who used principles learned from past games between master chess payers to design algorithms to decide what moves were best. These computer programs win against humans in large part by being able to: i) mimic the reasoned moves made by human master players, and ii) evaluate millions of possible moves before deciding on an actual move –a brute-force approach made possible by the much higher CPU clock speed of modern computers compared to the relatively slow speed of action-potential transmission along human neurons.

More recently, Stockfish was out-performed by a learning-capable computer program called AlphaZero (Silver et al. 2018) that used machine learning based on an artificial neural network (ANN). AlphaZero autonomously learned to win at chess by playing against itself for a mere 9 hours. Humans designed the structure and general learning algorithms of the ANN of AlphaZero, but the ANN program learned to win the game of chess without human assistance and without reference to previous games by human master players. Unlike the non-learning programs like Deep Blue and Stockfish, AlphaZero used many unexpected chess moves that were successful but unlike any previously recored moves in chess games between human experts. Collectively, these learning-incapable and learning-capable computer programs have became so proficient at playing chess that winning against the best human players has became a foregone conclusion.

We can consider the the various items that have been used to help in playing chess as utility-products that are 'chess assistants.' These utility-products have evolved from i) simple pieces of paper-like materials and books, to ii) computerized bookkeepers, to iii) an animated game displayer, to iv) an inferior chess opponent, to v) a superior chess opponent emulating human-learned strategies, to vi) a self-taught superior chess opponent with a unique style of playing and no learning input from humans. Put another way, the human/machine information spectrum (Figure 7) for the chess assistant utility-product has moved much of the way from the human pole toward the machine pole. This transition demonstrates the potential for utility-product paralife, in the form of complex machines, to become increasingly autonomous from the thinking of their human-associated life-forms.

The transition toward the machine pole of a human/machine information spectrum has also occurred recently in the context of basic scientific research. One of the fundamental problems in protein biochemistry over the last 50 years is understanding how to predict the three-dimensional configuration of a protein (i.e., its tertiary structure, or how a protein spontaneously folds into its final shape under cellular conditions) given the sequence of its component amino acids, i.e., its primary structure. The tertiary structure of a protein is important because it determines the biological function of most proteins. The solution for predicting tertiary structure from primary structure is an important question in protein biochemistry (a so called 'holy-grail') because we know the amino acid sequence of many hundreds of thousands of proteins (which will soon number many millions) but only in a very small proportion of cases do we know the corresponding tertiary structures. The tertiary structure is so rarely known because of the extreme cost (in time and funds for supplies, equipment and labor) of the empirical analysis needed to figure out the tertiary sequence of a protein. By using the limited number of cases where both the primary and tertiary structure of proteins is known, humans in many laboratories across the globe have tried to figure out how to predict the primary-to-tertiary structure conversion –with very little success despite 50 years of trying.

More recently, the company that developed AlphaZero for playing chess (DeepMind) developed an ANN to solve the protein folding problem (AlphaFold). In just a small number of years of total development time, AlphaFold learned to predict the tertiary structure of most proteins with very high accuracy (Senior et al. 2020). So the incorporation of AI in the form of self-learning ANNs has moved the laboratory computers in these protein biochemistry laboratories (a form of mechanical paralife) from far toward the human pole of a human/machine information spectrum a few years ago, to far toward the machine pole today in a remarkably short time. ANN-computers are expected to play a predominant role in the field of protein folding for the foreseeable future (Service 2020; Callaway 2020).

For machine paralife to become alive, its product must self-reproduce in an independent and automated manner by carrying out all seven core-SSR-functs. The examples of a cereal grain harvesting machine and the protein-folding AlphaZero ANN are not expected to evolve into this living state –no matter how automated they become– because they only function to harvest grain or fold proteins and not to reproduce themselves. However, a duo like i) the harvesting machine (or AlphaZero ANN-computer), and ii) the factory that makes it, has the potential to evolve into a self-sustaining reproduction system if the factory becomes fully automated and capable of producing not only their original products (harvester machines or ANN-software/ computers) but also the factories themselves.

To provide an example of substantial progress toward the machine pole of the human/machine information spectrum of a machine/factory duo, consider the FANUC robot-making factory located in Tsukuba, Japan (https://www.fanuc.co.jp/en/profile/production/index.html#tsukuba). This factory has a virtually completely automated manufacturing process in which robotic arms make robotic arms. If we took this factory one step further and had a robot-automated factory that made robotic arms and also produced (or continually remodeled) the factory that houses them, we would have a complex machine/factory duo that carries out all seven core-SSR-functs of a life-form.

In principle, we could design a robot-automated machine/factory duo to autonomously carry out all seven core-SSR-functs, e.g., autonomously use the internet to purchase required energy from an electrical grid, and autonomously purchase required raw materials from other factories, use robots to carry out maintenance operations, and so on. But such a fully automated machine/factory duo would nonetheless be a degenerate form of machine pseudo-life because it is intrinsically evolutionarily static and doomed to near-immediate extinction unless humans continually redesign it to accommodate a changing environment. It would also be unable to correct any spontaneous deterioration in the computer memory that stores its operation information (I).

The automated machine/factory duo would not be truly alive because although it would carry out all seven core-SSR-functs of a life-form, it would have virtually no evolutionary adaptive capacity (i.e., system-improving capacity) —except that generated by rare and system-improving copy errors in its system information (I, of its MIP-triad) component during remodeling. During its evolution to a highly automated state, virtually all of the evolutionary potential of the FANUC machine/factory duo was generated via human-generated thought-based modifications (the analog of biological mutations) coupled with human-based utility-selection (the analog of biological natural selection). Fully automating the machine/factory duo to carry out all seven life-functions would not replace these human-generated evolutionary functions –so the machine/factory duo would have nearly no adaptive evolutionary potential. To make a truly living machine/factory duo that is not dependent on human thought and oversight for its evolution, artificial intelligence within the machine/factory duo itself must replace the human intelligence that currently underlies the evolution of all mechanical paralife –no matter how fully automated they become.

The forms of AI thinking required for mechanical life

Human thinking is commonly described as having two major forms: intuition and reasoning (e.g., see Evans 2010). Intuition is fast but not logical. When using intuition, one makes a decision or conclusion without understanding how the decision or conclusion came about. For example, suppose that you are standing on a beach and see what appears to be the protruding head of something swimming nearby. You immediately think via intuition that you have seen a polar bear. This rapid decision was not logically motivated based on criteria like the presence of fur, the color of the fur, the size of the head, the color of the eyes, and so on: you just make a near-immediate, unreasoned and automatic classification decision.

Further suppose that the beach where you were standing was on an isolated tropical island. In this case, a second type of thinking –reasoning– would have generated a somewhat slower, tandem decision: you know that polar bears are only found in arctic waters and that no polar bears would feasibly be ectopically located anywhere nearby (e.g., in a zoo or animal park), so you make the subsequent deduction that what you saw was not a polar bear. At this point a new decision immediately needs to be made to fill the void created by your deduction –and it will necessarily be based on the limited information of what you can see from the beach. Such a decision would be an abduction such as: the head is most plausibly a swimming dog since you have seen large dogs with white fur on the island and dogs and polar bears have sufficiently similar head features.

The hastily generated abduction result has a high degree of uncertainty because it is based on insufficient information to make a high-confidence conclusion. As a consequence, you next imagine how you might resolve the uncertainty by iterating several what-if (I-did-this) cascades of potential actions: these are imagined simulations (ImSims) of what would happen if you began by carrying out various initial responses to a situation (Schacter and Addis 2020). This temporally cascading thought process (like watching an imagined short movie progress when you specify only the first few frames) draws upon both intuition and reasoning. It leads to an eventual plan that stimulates you to: i) carefully look at the protruding head, ii) form a detailed memory for subsequent consideration, and then iii) later use the memory of your careful observations to make a detailed comparison to field guides of the local biota. Based on this subsequent detailed comparison, you make the induction that the sighting was unambiguously a white morph of a monk seal (a rare form of a tropic mammal that inhabits tropical Hawaiian islands).

The above hypothetical example illustrates how the many forms of human thinking can be partitioned into components that are unreasoned (intuition) and reasoned (rational/logical). Reasoning can be further decomposed into deduction (from general to specifics), induction (from specifics to general), and abduction (plausible conclusions based on incomplete/insufficient information). The example also illustrates how thinking can take on a form of iterative 'what-if cascades' of potential actions (ImSims) that are used to decide how to act in the future and/or how to plan a path to solve a problem. Lastly, I point out that the example illustrates nothing new about human thought and its components (intuition, induction, deduction, etc.) that has not been described previously in elementary textbooks. Nonetheless, the example provides a reference point for the range of human thinking processes that AI in machine/factory duos would need to accomplish in order to fully replace human thinking in the context of the evolution (thought-based modifications and utility-selection) of mechanical life.

Although there are many approaches to machine learning in the context of AI, artificial neural networks (ANNs) most recently have been an especially productive approach in the context of visual and speech pattern recognition (Neilsen, 2015). In the context of replacing the human intelligence contribution to machine paralife (thought-based modification and utility-selection in machine/factory duos) to transform it to machine/factory life, ANN learning has to date made strong success in replacing some forms of human thinking and far more limited success in other forms. Using the swimming animal identification example described above, a machine at this point in time with a well trained ANN could effectively carry out the intuition part of the problem. However, most current-day ANN technology would do very poorly with the rational oversight part of the example in which reasoning first overrode intuition (with deduction) and then subsequently came up with a succession of logically superior alternatives (abduction followed by induction). It would also do poorly with the what-if cascades thinking (ImSims) that enabled a planned solution to made. Lastly, the advanced level of thought-based modification of UPs and utility-selection needed to produce the complex UPs associated with modern humans requires divergent thinking and creative imagination –as described in the companion paper (Rice 2022).

Some success in ANN reasoning has been made in the context of situations without a complex environmental context. For example, ANNs have been trained to deduce proofs for mathematical theorems (Guilhoto 2018; Lample and Charton 2019). Until very recently, however, most forms of human reasoning have not been well replicated in ANNs nor any other form of machine learning. Nonetheless, the fact that biotic NNs in human brains carry out both intuitive and rational thinking, and given the substantial prowess of

ANN over human NN in the context of intuitive decisions in games like chess and the example of solving the protein folding problem, there seems little doubt that substantial progress in AI-reasoning is inevitable in the future. Recent examples of substantial success in a forms of fast-acting ANN reasoning (e.g., Santoro et al. 2017; Devlin et al. 2018; Slonim et al. 2021; Vaishnav et al 2022) indicate that machine/factory duos with powerful reasoning-AI may develop in the not-to-distant future, i.e. within decades rather than centuries.

An expected gradual transition to mechanical life

As AI-reasoning and factory automation improve over time, there will be an inevitable shift in machine/factory duos toward the machine pole of the human/machine information spectrum. Like the FANUC robot-making factory described earlier, future factories will become increasingly automated across time and depopulated with humans (e.g., see Keynes 1932; Acemoglu and Restrepo 2020). Replacement of simple repetitive manual labor with robots is a straightforward extrapolation, including labor tasks requiring predominantly intuitive thinking like some types of assembly-line workers and drivers of vehicles. But replacing human workers that must carry out complex rational thinking is expected to be more technically difficult –and therefore slower.

As AI-reasoning becomes more sophisticated and capable, reasoning-requiring workers (e.g., decision-making executives/administrators, engineers and scientists) would be expected to increasingly rely on AI-reasoning machines as AI-assistants –simply because those that do so will perform better at their jobs and competitively replace those that do not. For example, personal computers were rare among reasoning-requiring workers in the 1970s but nearly universal 'personal assistants' by the year 2000. However, just as in the chess-player / UP-assistant pairs (and the protein biochemist / UP-assistant pairs) described in an earlier section, administrator, engineer and scientist human/AI-assistant pairs will move progressively more toward the machine pole of the human/machine information spectrum –until, like chess and protein folding, humans are out-performed by their AI-assistants (machines).

Once humans become substantially outperformed in human/AI-assistant pairs, factory/product duos, like the one described earlier for the cereal grain harvester, will have become become truly 'alive' because the AI controlled factory will have become both completely automated and also capable of autonomously carrying out the thought-based modification and utility-selection needed to adjust in response to environmental change or deterioration in their production information (I), i.e., capable of self-improvement via rapid system-improving evolution (Supplemental Figure S1). As the rational-AI capacity of machine/factory duos increases, they will be able to produce increasingly complex machines and factories: leading to an expansion of the structural complexity of both the factories and the machines (complex utility-products) that they produce.

Another route to machine life (besides machine/factory duos) concerns utility-products that are designed to be deep thinking and autonomous. For example, consider the case of utility-products that are personal assistants. Initially these were simple recording devices likes pieces of paper (Supplemental Figure S2, top-left). With time they evolved into books, personal computers/smart-phones, and intuition-capable AI-assistants (Supplemental Figure S2, large arrow at bottom-left). Eventually reasoning-capable AI-assistants would be expected to evolve. Once the reasoning capability became sufficient, such an AI-assistant would be capable of controlling robotic arms (as drones) to continually repair and update its hardware and software, carry out all seven core-SSR-functs, and also do the thinking behind its reasoned modifications and utility selection, i.e., it would become a self-sustaining system capable of reproduction and system-improving evolution and therefore constitute a form of mechanical life in which replication is replaced with remodeling by drone-like robotic mechanisms (Supplemental Figure S2, right). Personal assistants are unusual utility-products/machines because they would be engineered to be deep thinkers that are able to interact with humans in the context of complex problems –including social interactions. Such interactions would require the ability to perceive and process subtle nuances in human language (non-literal pragmatics), behavior and social interactions, as well as the rational and irrational thinking, emotions and pleasure/pain experienced by their associated humans. As such, they would

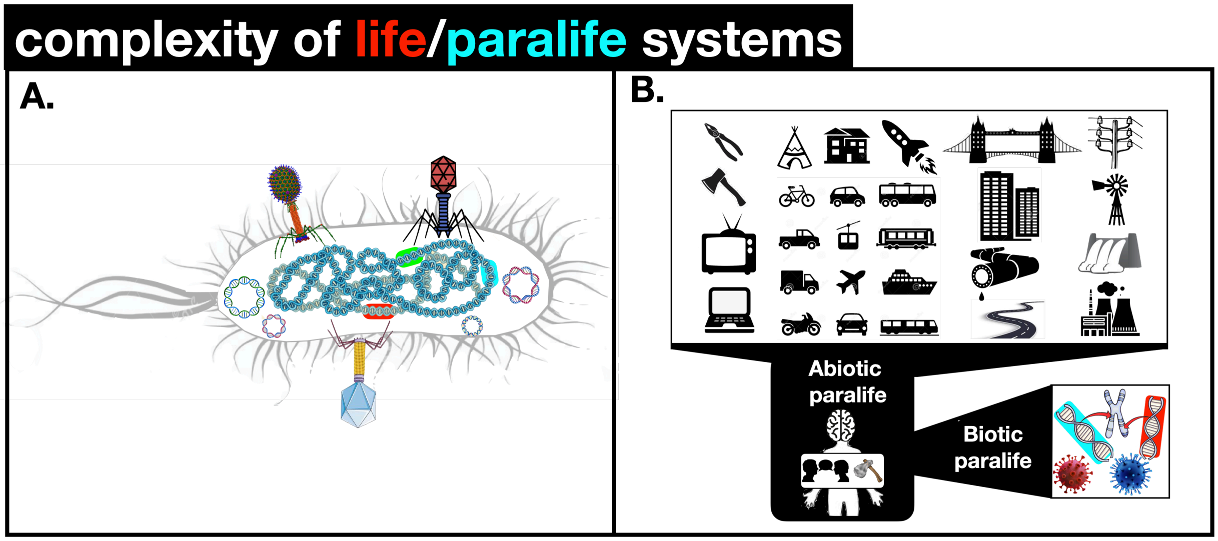

Figure 8. The complexity of life/paralife systems. **A.** For non-human biological life (e.g., a bacteria), the total complexity of an organism spans that of i) the organism itself, and ii) its associated biotic paralife. **B.** For humans, the total complexity spans that of i) the organism itself, ii) its associated biotic paralife, and iii) its associated UP-paralife (abiotic paralife). Because UP-paralife is so diverse, and in some cases highly complex, total structural complexity of humans far exceeds that of other biotic life forms. In (A), i) the long twisted string-like structure represents the bacterial chromosome, ii) back-colored regions of the bacterial chromosome represent transposons, iii) small circular double-helixes represent plasmids, and iv) bacteriophage are shown attached to the bacterial cell wall. In (B), studded spheres represent viruses and back-colored double-helix segments represent transposons embedded in the X-shaped duplicated chromosome icon.

be designed to be among the smartest AI-thinking utility-products that are especially capable of acting autonomously and continually maintaining, remodeling, and replacing themselves, i.e able to carry out all of their core-SSR-functs, reproduce themselves via remodeling, and control their own system-improving evolution via reasoned modifications and utility selection.

The role of mechanical paralife in expanding structural complexity

The level of structural complexity within the universe increased to a high degree when life first evolved and continued to increase as major evolutionary transitions generated increasingly more complex biological organisms: reaching a pinnacle in human societies (Szathmary and Maynard Smith 1995). The structural complexity of a biological organism encompasses a system including the organism themselves and all of the paralife forms that are inherently associated with them (Figure 8A). For example, a hypothetical bacteria that lacked all forms of paralife (plasmids, transposons, and viruses) would be less structurally complex than an identical bacteria that included a wide diversity of paralife forms (Figure 8A). Compared to other cellular organisms, humans have a greatly expanded system of associated paralife because they have both biological paralife (transposons and viruses) and a wide diversity of UP-paralife (all types of utility-products; Figure 8B). To a much more limited degree, structures like bird nests, bee hives, and beaver dams also add to the structural complexity of some animal species systems. These structures, however, are far more limited in number and complexity compared human paralife because they are based predominantly on instinctual (genetically coded by the biological organism), non-learned information, i.e., they are not UP-paralife and lack its open-ended potential for expanded diversity and complexity.

The extreme number of different types of UP-paralife, and the high complexity of many types of machines (reaching a current pinnacle in machines like super-computers, artificial suns, and large particle colliders) has caused the structural complexity of the human life/paralife system to greatly exceed any other biological life form. Assuming that advances in machine reasoning will expand the complexity of the mechanical paralife that becomes integrated into the human/paralife system, the advent of UP-paralife will have initiated a continuously expanding level of structural complexity that far

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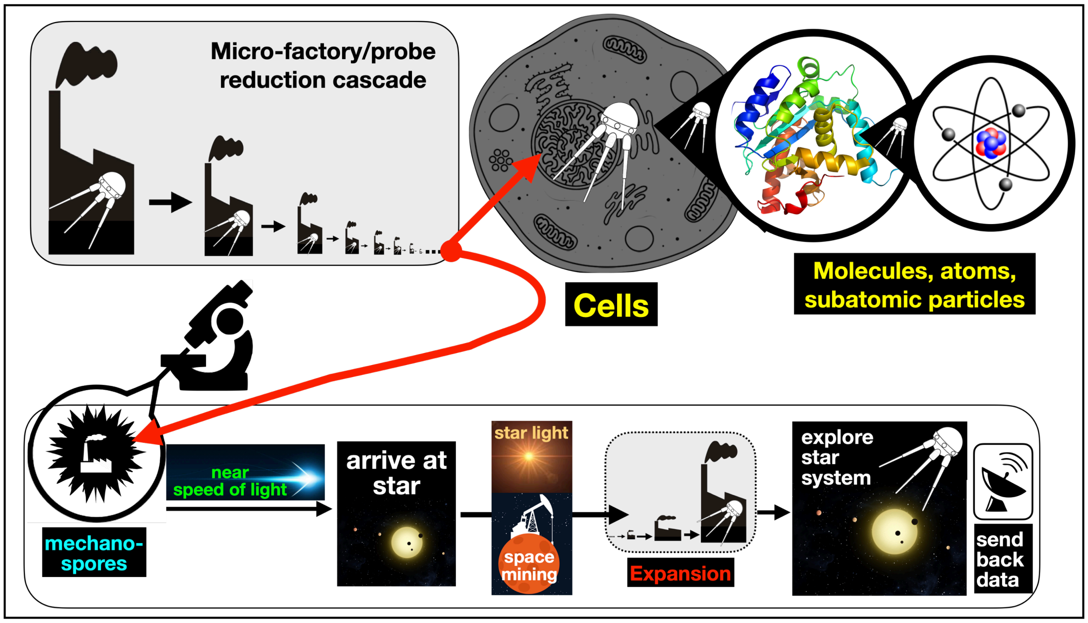

Figure 9. Future AI-reasoning machine/factory duos plausibly will be scaleable to very small size (microscopic machine/factory duos) via the construction of a succession of progressively smaller scale duos (top-left). **Top-right.** This down-scaling will allow complex AI-reasoning-probes (circular structure with three legs) to be manufactured that enable phenomenon that are very small to be observed and measured with much less magnification compared to the present day. **Bottom.** Micro-machine/factory duos also plausibly could be packaged within micro-rockets used to explore astronomical phenomena. The micro-machine/factories duos would be 'mechano-spores' because they could reverse the miniaturization process and expand back to their original size –just as the minute spores of a fern or fungus ontogenetically grow to become a full-sized adult. Such micro-machine/factory/rockets would, due to their extremely small size, plausibly be able to be accelerated to speeds near the speed of light (e.g. via magnetic field accelerators) and sent to nearby stars and satellite galaxies. Upon arrival, light energy from the star could be captured and resources from its orbiting materials could be mined to expand the micro-machine/factory duo back to a size needed to produce the AI-reasoning probes needed to explore the star system and send back the acquired information. These outposts could also manufacture and launch (at near the speed of light) micro-machine/factory/rockets to more distant stars that were not accessible from Earth due to intervening space objects, and also act as signal repeaters to transmit information from these more distant stars back to Earth. In this way the entire Milky Way galaxy, and its nearby satellite galaxies, could be fully explored within a few hundred thousand years – a relatively short time for AI-machine-scientists that can persist indefinitely with continuous repair and remodeling.

exceeds that of biological-life/biological-paralife systems alone: thereby greatly expanding the level of structural complexity that has evolved within the universe. As described later in the Discussion section, the evolution of machine life is expected to generate another major expansion of structural complexity.

The role of mechanical life in scientific progress

One of the major limitations in science is the need for extreme magnification to observe and measure phenomenon that are very small (e.g., cellular substructures, molecules, atoms, and subatomic particles) and very far away (e.g., astronomical objects like astroids, comets, planets, stars, and galaxies). Mechanical life is expected to circumvent much of this magnification limitation by an extreme reduction in machine size that precludes the need for extreme magnification.

Physiological constraints strongly limit the size of temperature-controlled animals like humans: endothermic mammals cannot function at a size much smaller than the common shrew (the size of small mouse). In principle, however, AI-reasoning machines, and the factories that produce them, could be scaled-down to extremely small sizes that are a great many orders of magnitude smaller than humans. Such AI-reasoning micro-machines, when designed to be scientific probes (rational machine-sensors), would require much less magnification to observe, measure and analyze phenomena that are far too small to observe with microscopes –and indirectly, telescopes.

Construction of complex micro-machines by humans is constrained by limitations of scale. Although current advances in nanotechnology clearly demonstrate a capacity of humans to construct and design minuscule material objects, construction of complex machines at this size scale are unlikely to be possible. In principle, machine/factory duos should be able to be progressively down-scaled: thereby enabling the the production of complex machines far smaller than presently possible.

Consider a machine/factory duo with AI-reasoning that produced probes for scientific research that are capable of AI-reasoning. A succession of AI-machine/factory reductions (Figure 9) would mimic an infinity mirror (a configuration of two parallel facing mirrors that generates a succession of increasingly smaller reflections that appear to recede to an infinitely small image). Numerous adjustments would need to be made at different size transitions to account for processes that change with scale (e.g., the distance or voltage needed to insulate nearby electrical conductors on a circuit-board) –so the reduction cascade would be a major engineering undertaking that would need to be solved by successively smaller machine/factory duos with AI-reasoning. As the machines/probes became increasingly reduced in size, less magnification would be needed to observe small-scale phenomenon and measurements of their characteristics would be improved –thereby increasing the scope of knowledge acquisition of small-scale phenomenon (Figure 9, top).

Microscale machine/factories would also plausibly revolutionize the study of far away phenomena like those studied in the field of astronomy and astrophysics (Figure 9, bottom). In this case, AI-machine/factory duos with extreme down-sizing plausibly could make possible space travel at near the speed of light: thereby make the scientific exploration of nearby star systems plausible on a tractable time scale. Instead of sending one or a few slow-moving, large-scale space ships loaded with complex machines and robots (or less realistically humans) to explore distant star systems in our Milky Way galaxy and nearby satellite galaxies (analogous to the early 21st century robotic-explorer missions to Mars, but without control via two-way communication), large numbers of micro-scale AI-machine/factory duos (packaged within micro-rockets) could be launched that were propelled by mechanisms like nanoparticle electric field propulsion (Gallimore and Gilchrist 2006) or magnetic field accelerators (Tzeng 2004). These propulsion mechanisms would feasibly be able to accelerate the micro-AI-machine/factories/rockets to near the speed of light and then release them in a direction aimed at a target star or satellite galaxy (many replicates aimed at each target). The micro-AI-machine/factories/rockets would need to be programmed to periodically adjust their trajectory and eventually decelerate and fully activate after arriving at the target star.

Once activated, the micro-AI-machine/factories could use star light energy from the destination star to begin manufacturing a succession of larger-scale copies of itself, i.e., they would be mechano-spores that are the equivalent of the minute biological spores of ferns and fungi that undergo ontogeny to develop into much larger adults (or the development of a single fertilized egg cell into a much larger, multicellular adult). The raw materials needed for the manufacturing process would be obtained from mining materials (cosmic dust, meteorites, etc.) that were orbiting the star. Once a sufficiently larger-scale AI-machine/factory was produced, it would start manufacturing the infrastructure needed to explore the star and its satellites of all sizes (cosmic dust to planets), and also send the collected information back to Earth. The AI-machine/factory would also manufacture and send (at near the speed of light) mechano-spores to more distant nearby stars when these were not accessible from Earth due to features like intervening cosmic dust and other interfering contexts. Because of both the near speed-of-light dispersal of the mechano-spores/rockets and the full speed-of-light transmission of information back to Earth (or intervening, already explored star systems acting as signal repeaters), the entire Milky Way galaxy (about 1,000 light years across) and its nearby satellite galaxies could be explored in a matter of a few hundred thousand years: a short time on a universe-level time scale, and a time scale at which AI-machine-scientists could potentially operate.

Discussion

Nearly all material objects can be unambiguously and intuitively assigned to a dichotomy of animate life and inanimate non-life (Figure 1) –with only the biological sub-cellular plasmids, transposons and viruses occupying an intermediate classification of paralife (near-life). To explore the possibility of non-biological forms of life and paralife, I needed to produce functional definitions of life and paralife that had universal application because they were based solely on functioning and independent the specific structural features of life and paraife on Earth. I began with the observation that all unambiguous forms of life on Earth function as non-spontaneous reproduction systems that are self-perpetuating (continue to function indefinitely without outside assistance). I then showed why being a non-spontaneous reproduction system that is self-perpetuating requires a set of seven core self-sustaining reproductive functions (core-SSR-functs) that are essential for any form of life –not just biological life as it evolved on Earth. Self-perpetuation also requires that: i) the system make copies of itself in order to counteract deterioration of system functioning due to senescence and/or a complete breakdown in functioning (death), and ii) have an evolution process that is system-improving in order to counteract a changing environment and/or entropic disordering in the system's physically-encoded operation information. Combining these intrinsic functional requirements for life produced a functional definition of life and paralife. The definitions are identical except the term 'functioning' in the definition of life is replaced by the term 'inducing functioning' in the definition of paralife. This term change reflects the fact that paralife induces a life-form to carryout all or some of the seven core-SSR-functs needed for self-sustaining repair and reproduction (Figures 3 and 5).

Applying the definitions of life and paralife to non-biological material objects leads to the counterintuitive conclusion that human-made utility-products (tools, clothing, housing and other material objects that are fabricated by humans using learned information because they are useful) are part of a UP-paralife system that: i) has a mutable and physically-encoded heredity system and heritable phenotypes, ii) induces humans to use their seven core-SSR-functs to reproduce them due to their perceived usefulness, and iii) evolves in a nonrandom, system-improving manner. Because the induced-reproduction systems of utility-products do not include all seven core-SSR-functs needed to produce copies of themselves, and because their evolution requires the thinking of their human symbionts, they will remain para-alive until they evolve these capacities.

Utility products in the form of machine/factory duos or personal assistants are currently evolving toward becoming fully alive because they are evolving the capacity to replicate themselves and control their mutation and selection processes (Supplemental Figures S1 and S2). More specifically, factories are becoming progressively more automated and an increasing proportion of the production information (for utility-product/factories) is stored in computer memory: causing the role of humans in utility-products to progressively shrink. To eventually reach the stage of machine-life that is capable of human-free evolution via thought-based modifications and utility-selection, machine/factory duos or mechanical personal assistants, will need to develop a form of production-controlling AI that goes beyond the current emphasis on AI-intuition to a form of AI-reasoning and capacities for imagination and creativity based on divergent thinking (see the companion paper [Rice 2022] for a detained discussion). Recent progress in the skill level of AI intuition and reasoning suggests that machines are rapidly moving toward being able to out-perform humans in both respects. Once AI-thinking becomes sufficiently developed, it seems inevitable that machine-life will quickly follow.

One feature that makes the conclusion that utility-products are para-alive counterintuitive is the fact that part of the the material product (P_1, the utility-product) is separated from the part which encodes the production information (P_2, a NN engram within a human's brain) –unlike biological organisms in which the hereditary information is embedded within the cell(s) of the organism (Figure 5). However, this dissociation is also true for some forms of biological paralife: in plasmids and transposons some components of the product (e.g., proteins like transposases and col-factors) are never co-packaged with the hereditary nucleic acids. It is also true that as utility products become progressively more complex and are manufactured in factories (especially those that are automated), most of the information component of mechanical paralife migrates out of human NNs and into mechanical memory storage that is associated with the utility product (machine) and/or its manufacturing factory.

The evolution of life was a major milestone that generated a quantum leap in the level of complexity of material objects in the universe (Dalgarno 2006; Szathmary and Maynard Smith 1995; Lehn 2013; Wolf et al. 2018). The evolution of UP-paralife has greatly expanded this level of complexity (Figure 8). The eventual evolution of mechanical life in the form of reasoning-AI controlled machine/factory duos and mechanical personal assistants is expected to substantially increase this level of complexity.

Consider a form of mechanical life in the form of a fully automated, AI-reasoning scientific research institution. AI-reasoning machine/factory duos that range in size from microscopic AI-machine-probes to a network of space probes that span the Milky Way galaxy (Figure 9) could be integrated into the same system of research units. This system would integrate ultra-complex complex machines that ranged in size from a network of self-assembling/thinking space probes, that spans 5 x 10^{17} kilometers across the Milky Way galaxy, to probes small enough to observe hydrogen atoms (10^{-13} kilometers) without extreme levels of magnification. Such an integrated system of complex machine-life with billions of parts and spanning over 25 orders of magnitude in size and many trillions of kilometers of space would dwarf the complexity of life-forms on Earth, including the current system of humans with their biological and mechanical paralife.

Lastly, I point out that the logical progression described here predicts that all forms of chemical-system life that evolve anywhere in the universe, and that evolve life systems that are tool-making and language-capable, would be expected to evolve toward AI-reasoning mechanical life, which would displace intelligent chemical-system life with respect to the life systems responsible for advances in science and technology. As a consequence, advances in science and technology via intelligent chemical life would be expected to be a short-term transient. Therefore any search for intelligent life should include a search for long-range signs of the activities of mechanical life (mechano-scientists/engineers which, in principle, can persist indefinitely by continuous remodeling). Mechanical life does not require the same environmental conditions needed for water-based chemical life and may presently exist where chemical life similar to biological life cannot.

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Supplementary Figures on on the following pages

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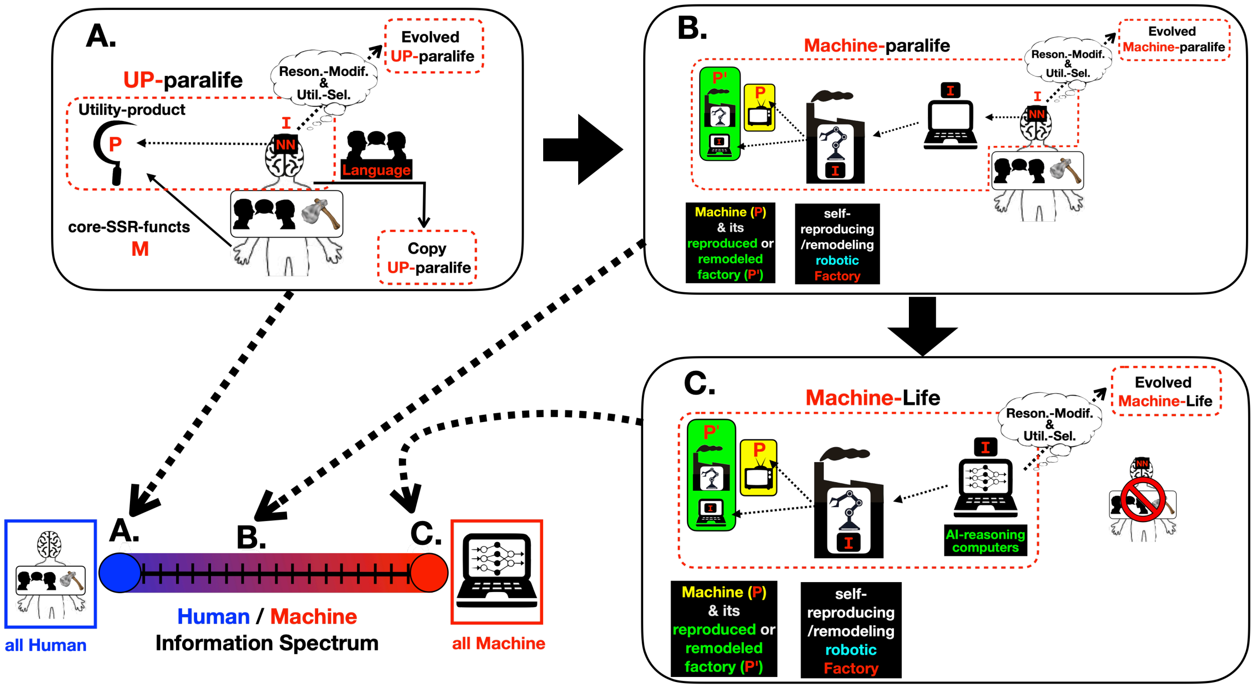

Supplemental Figure S1. As utility-products increase in complexity, the human/machine information spectrum moves progressively toward the machine pole because i) its production information, and ii) the thinking behind the production process, and iii) its evolutionary change (via thought-based modifications and utility selection) moves progressively more out of human NNs. **A.** UP-paralife in which the production system makes a simple utility product (sickle hand tool) where all of the production information (I) is in a human NN, as is the thinking responsible for production and evolution. **B.** Machine-paralife in a more complex machine/factory duo (making a television in a highly automated factory) where most of the production information (I) is in computer memory, as is most of the thinking responsible for production, but none of the thinking for its design and evolution. **C.** Machine-life in a more complex machine/factory duo (making a television in a highly automated factory that is controlled by a reasoning-AI computer): here all of the production information (I) is in computer memory, as is all of the thinking responsible for production, and all of the thinking for its design and evolution. At this point the machine/factory duo is life rather than paralife.

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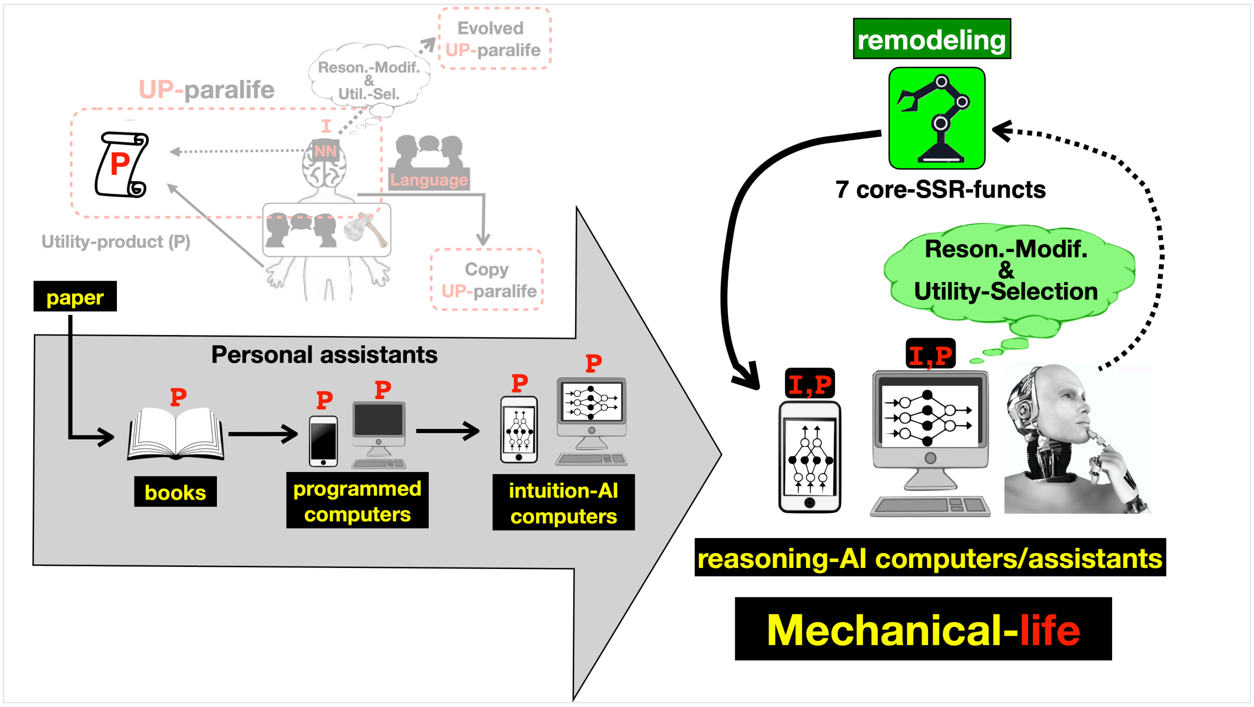

Supplemental Figure S2. A second route to mechanical life, besides automated machine/factory duos with reasoning-AI control, would plausibly be machines that evolve to solve complex problems with AI-reasoning: like a personal assistant to a human. Human personal assistants began as simple pieces of paper-like materials (labeled as paper) with hand-written information (top-left) but progressively evolved to become more complex machines (grey arrow on bottom-left). Once these machines developed reasoning-AI that was capable of controlling drone-like robots for self-repair and remodeling (and all core-SSR-functs), and also the ability to redesign itself via reasoned modification and utility selection, it will have become a machine that meets the definition of life, and hence it will have become alive.