Humankind on the Verge of Becoming a Spacefaring Civilization

Introduction

The action is set in the year 2328, in the system of the double star BD–05 1844 (or Gliese 250) at 28.4 light years (9.2 parsecs) from the Sun[1]. The primary star, BD-05 1844 A is an orange-red dwarf star (K3V), with a mass about 80 % of the mass of the Sun but a luminosity of only 14.6 %. BD-05 1844 B is a red dwarf, (M2.5V), with 50 % the mass of the Sun and only 0.58 % of its luminosity. Their separation is about 500 Astronomical Units.

Its apparent magnitude is + 6.58 and thus it is essentially invisible to naked eye observers. No exoplanets have yet been discovered orbiting this double star, so the planets (and their moons) mentioned in the novel are fictitious.

The model assumed to assess the science and technology at that time in the future is an evolutionary model: Technological advances occur through a slow refinement of the technologies and of the scientific theories that underlie them. Scientific revolutions are rare and technological revolutions even rarer. Sometimes a number of fields of technology may have a rapid development, followed by a period of stasis in which little happens, while other fields begin a dramatic advance. An example of this is the period between 1935 and 1965 for aviation and then space travel. In 30 years humans passed from propeller-driven biplanes to supersonic jets to and rockets that allowed them to land on the Moon. The nuclear rockets that would have allowed humankind to become a spacefaring civilization were even tested on the ground. Then in the following 45 years little happened, or worse, there was a setback. As we know, a heavy lift rocket such as the Saturn 5 no longer exists, the Space Shuttle has been scrapped, the supersonic airliner is no longer operational, and nuclear rockets have not materialized.

When in 2004 a return to the Moon was seriously being considered by NASA, the Constellation program, which included the launchers Ares I and

[1] It lies in the east central part (6:52:18.1-5:10:25.4 for Star A and 6:52:18-5:11.4 for Star B, ICRS 2000.0) of the constellation *Monoceros.*

G. Genta, *The Hunter*, Science and Fiction,
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V and the spacecraft Orion, was initiated. It was mainly based on technologies similar to those that 40 years ago allowed humans to reach the Moon but, mainly for cost reasons, the whole program was canceled in 2010.

While aerospace technology has not made the quick steps forward that were predicted, we have had striking advances in computers, electronics, cell phones, etc. True innovation is usually unpredictable. For instance nobody predicted the diffusion of ICT such as personal computers, cell phones and the internet, while many advances in other fields, which were predicted to happen in the near future, never materialized.

The science and technology described in the novel are not very advanced, except for assuming a single 'scientific revolution' that fuels a 'technological revolution': the warp drive. This propulsion device allows humankind to start a true interstellar spacefaring civilization, expanding in a sphere with a radius of about 9 parsecs centered on the Sun by the time in which the novel is set.

The main scientific aspects that enter this novel are related to robotics: some characters actually are robots, and the villains of the story are robots, those still hypothetical robots usually referred to as *Von Neumann machines*.

Space Travel

The basic assumption I make is that little useful work can be done in space using chemical propulsion. After the race to the moon of the 1960s and 1970s, the present stagnant situation is assumed to have lasted until about 2020, when space exploration resumes thanks to private investors developing space tourism and, later, asteroid mining. A further assumption is that nuclear propulsion, derived initially from the old 20th century studies [1, 2] and above all from the nuclear rocket built and tested on the ground as a part of the NERVA program, allows humankind to reach Mars and nearby asteroids in a reasonable time, and is also instrumental in making faster and cheaper journeys to the Moon.

Mars is assumed to be a barren desert, with no life at all, and plans for terraforming the planet are drafted as soon as the absence of indigenous life is ascertained. In the novel, the expansion in the Solar System proceeds with slow improvements until the end of the 21st century, with the noteworthy application of nuclear fusion to space propulsion. This results in opening up the main asteroid belt to exploitation.

Theoretical ideas on propellantless propulsion and warp drive were advanced at the end of the 20th century [3–5]. In particular, the Breakthrough Propulsion Physics (BPP) program [6], which focused more on physical and mathematical aspects of advanced space propulsion than on applications, was active between 1996 and 2002. Its goal was to lay out the scientific foundations of what could become a new technology some decades from now—*to perform credible progress toward incredible possibilities,* as the catch phrase of the program said. In 2013 NASA resumed studies on a warp drive, and in the novel it is assumed that new advances first allowed a better theoretical understanding and then the development of a technology allowing FTL (Faster Than Light) interstellar travel.

Propellantless propulsion (or space drive) is assumed to be achieved first, allowing humankind to draw up plans for interstellar colonization journeys at speeds lower than that of light. However, before these plans could be implemented, I make the assumption that the first warp drive starship was launched and a FTL probe sent to Alpha Centauri. Colonization of nearby exoplanets could thus be started with journeys lasting months instead of many years or centuries.

A further assumption is that a technology for controlling gravity may be obtained from the same hypothetical development of physics that enabled propellantless propulsion. Artificial gravity could thus be created on board starships (on space stations the same goal is obtained by rotating the station to save energy), with the added advantage of compensating for the high accelerations needed to reach speeds comparable with the speed of light in a reasonable time.

Such fast starships (in this fictional world as well as in the real world) would have to be provided with shields to prevent damage from collisions with micrometeoroids and other objects. The same shields can also be used as a protection against weapons, something needed—in the novel—since the rapid expansion of human civilization at rapidly increasing distances from Earth produces an unstable situation in the frontier zones where the novel is set. There, encounters with unfriendly people—humans, since no aliens will be encountered at those (astronomically close) distances from Earth—are by no means rare. At the time at which the events described occur, the presence of hostile replicators (see below) will disrupt the peaceful order of society, increasing the probability of such encounters.

Warp drive requires huge quantities of energy and in the novel a solution is found for storing energy on board. Antimatter is produced from deuterium and helium-3 mined from the atmosphere of gas giants and burned in fusion reactors. Antimatter is then stored in huge space stations orbiting the same planets and used as an energy medium to power starships.

Using warp drive, journeys among systems separated by a few parsecs may take some weeks. This duplicates the situation on Earth in the 17th and 18th centuries, when transoceanic travel was slow and costly—but possible, nevertheless, thus allowing empires spanning different continents to be built.

Colonies can therefore be built on some extrasolar planets but, since in the novel extraterrestrial life is assumed to be rare, open-air settlements will be started on just a few planets because of the lack of suitable biospheres supporting an atmosphere rich in oxygen. Most of the planets need thus to be terraformed, and this process is assumed to be started in several places, mostly by private terraforming and space engineering companies. One of these companies, partially owned by the Chinese government, is said to start terraforming operations on a terrestrial planet orbiting Gliese 250 A in 2270.

At present, the science and technology that will allow terraforming planets are still in their infancy and it is uncertain how it may proceed. What is certain is that the complexity and the approach required are strictly dependant on the characteristics of the planet. In the case of Mars, for instance, terraforming operations can be divided into two phases—increasing the atmospheric pressure, perhaps by heating the surface, and making the air breathable [5, 7]. The whole operation may take a very long time, but some estimates as short as 500 years have been proposed [7]. Shorter terraforming times may be made possible by the use of nanotechnologies.

Recently, the idea that even small and airless worlds like the Moon may be terraformed has been considered. Owing to its small mass an atmosphere cannot be made stable, but the time needed for the Moon to lose an artificial atmosphere may be so long that a modest amount of gas released continuously would be able to compensate for the losses.

In the novel, the terraforming processes on a number of explanets, like the one assumed to exist in the Gliese 250 system, are described as being under way. However, since it seems that the number of exoplanets is very large, some selected planets with favorable characteristics that can be terraformed in a short time are assumed to exist.

Another assumption is that progress in materials will allow the construction of space elevators [8] within the timeframe described in the novel. However, owing to the cost of such infrastructure, only the Earth and a few colonized planets are assumed to have traffic between the surface and space, allowing a space elevator to be cost-effective. Moreover, the cost of space transportation is assumed to be quite low, mainly thanks to the use of nuclear propulsion, not only beyond Earth orbit, but also in the last part of the satellization run. Under such circumstances it may be expected that the volume of traffic that can justify a space elevator is very high indeed.

Another idea that permeates the novel is that the starting of a spacefaring civilization will have a strong effect on humankind. Interbreeding will cause human races and differentiated cultures to almost disappear and a single human type will start to emerge. This is reflected in the names of the characters, which are often a mixture of what today are names and surnames from different cultures and nations. However, new differences are assumed to start emerging between people living on high- and low-gravity planets, or in high- or low-pressure atmospheres [9]. This latter process is much slower than the effects of interbreeding, and at the time the novel is set it is assumed to be still marginal.

Astrobiology

The basic astrobiological theory followed in the novel is what is usually called the "Rare Earth Hypothesis": Life is fairly common in the universe, but only at the level of its most elementary types [10]. The possibility that no complex life exists within 10 parsecs from Earth is not surprising, as even the most enthusiastic supporters of SETI (Search for Extraterrestrial Intelligence) would readily agree. By introducing very optimistic numbers into the Drake equation, the result is an average distance between intelligent species of about 200 parsecs. The astrobiological background of the novel is thus consistent with today's mainstream astrobiological thinking [11].

In the novel, then, a number of planets in the range of 9 parsecs from Earth (i.e. within the colonized zone) are assumed to possess an elementary kind of life which, in some cases, has transformed the atmosphere, enriching it with oxygen and making it breathable (or almost breathable) by humans. This is the case, for instance, of Ceres, a fictitious Moon of a planet orbiting Gliese 250 B. This moon could be colonized easily, without the need for being terraformed (unlike completely sterile planets, which are assumed to be the majority). As a consequence, since terraforming is a long and costly process, particularly in the case of hostile planets, the colonized zone is said to contain few inhabited planets. Most settlements are described as small space stations or mining bases on asteroids.

As already stated, nothing is known about possible planets in the Gliese 250 system. In the novel the system is assumed to contain several planets, two of which are particularly interesting, and asteroids. The first of the interesting bodies is a large terrestrial planet, orbiting the A component, which hosts no life forms and is being terraformed. This planet lies in the habitable zone of the star, quite close to it, but is not gravitationally locked so that, once terraformed, it may become an important center in the frontier zone.

The second is the satellite of a giant planet orbiting very close to the B component of the star. It has a very primitive biosphere, consisting of just bacteria, that have enriched its atmosphere with oxygen and made it directly habitable. At the time in which the action of the novel is set, the body has been settled and terrestrial life forms introduced. The ethical problems linked with the subsequent, almost certain, extinction of the indigenous forms of life are not discussed, but it is clear that the company that owns the body, and wants to use it as a logistics center for terraforming the other planet, does not care much for the subject. It set up a sealed enclave in which the local forms of life are preserved for scientific reasons, but that is all. In the frontier zone, at 9 parsecs from Earth, there is nobody who can enforce rules for the protection of bacterial forms of life. And, after all, we know that humankind has caused the extinction of bacteria or viruses, such as the virus responsible for smallpox, without too many ethical qualms!

No planet in the colonized zone (nor seemingly in the known Universe) is believed to contain higher forms of life. For centuries the common opinion was that the only place in which complex life, and then intelligent life, could evolve, was Earth. This belief is shaken in year 2294, about 30 years before the time at which the action in the novel takes place, when mysterious self-replicating robots are found: if they are artificial, as most people believe, then some alien species must have built them. However, some characters in the novel still oppose this theory, suspecting that the *replicators*, as these robots are called (see below), evolved by themselves, without being built by anyone.

Robotics

Robots and artificial intelligence

The term 'artificial intelligence' was first used in a conference held in the summer of 1956 at the Dartmouth College, New Hampshire, and has been widely used ever since. Although no commonly agreed definition of artificial intelligence (or, for that matter, human intelligence) exists, there is general agreement in accepting that it consists of a machine imitating human intelligent behavior. The well known *Turing test* comes closest to a definition: a machine is intelligent if it is impossible to distinguish it from a human being during an interaction based on exchanging messages on any subject.

Two methods have been employed to reach the goal of creating artificial intelligence. The first consists in writing dedicated software running on conventional, although very powerful, computers, able to manipulate symbols following well-established rules. The basis for these attempts is the assumption that intelligence is based on algorithms that perform logical operations by manipulating symbols. The human brain is thus considered to be a biological computer, and the human mind is the result of some sort of software running on it. This method supposes that intelligence and even consciousness can be obtained by using a non-biological computer, provided it is powerful enough to run suitable software.

The second approach is the neural one, based on the construction of a network of artificial neurons, simulating the structure of animal, and also human, brains. The Artificial Neural Networks (ANN) so devised operate not by running programs but by learning.

These two approaches are not as different as they look, because the operation of neural networks may be simulated on a computer, i.e., it can be reduced to software running on a conventional machine. In this way the second approach seems to reduce to a particular case of the first.

At any rate, the neural approach seemed to be haunted by unsolvable problems and at the end of the 1960s it seemed to be a dead end. The algorithmic approach, on the other hand, seemed to obtain encouraging results.

By the mid 1980s the neural approach regained momentum when the above-mentioned problems were solved, but the goal of building intelligent and conscious machines proved to be much harder than predicted. In the 1960s it was a common opinion that by the year 2000 there would be an established technological result. At the time of writing, in 2013, artificial intelligence seems still to be far away and many scientists cast doubt on its feasibility, at least with present-day technology [12].

A tentative scheme of the path leading from inert matter to intelligent and conscious systems is shown in Fig. 1 [13]. According to this scheme, a material system, able to manipulate energy, is a dynamic system. If it can also receive signals and manipulate information, it may be considered as an automatic device, and so on. It is debatable whether the decision box should be over or under the knowledge box. Here it is assumed that a being (living or robotic) can take decisions reacting to the inputs from the outer world even without building an internal model of it. This point has been controversial, but here it is assumed that a positive answer to this problem is realistic. Moreover, sometimes it seems that there is no complete agreement on the meaning of the terms in the boxes, so that the answer depends on the exact interpretations of what the words 'knowledge' and 'decision' mean.

The boxes on the right should not be considered as separate steps in a ladder, but rather as levels in a continuous evolutionary process, and there is an infinite number of shades between each of them.

Telemanipulators, i.e. remote controlled agents able to perform well-determined tasks, are without any doubt at the second level—they are *automatic systems*, as are many other automatic machines of various kinds. In many cases, telemanipulators display some form of limited autonomy, being able to take low-level decisions, while being controlled by humans for higher-level tasks [13].

The earliest manipulators, used for the preparation of radioactive materials, were purely mechanical devices, consisting of an arm and a gripper, able to

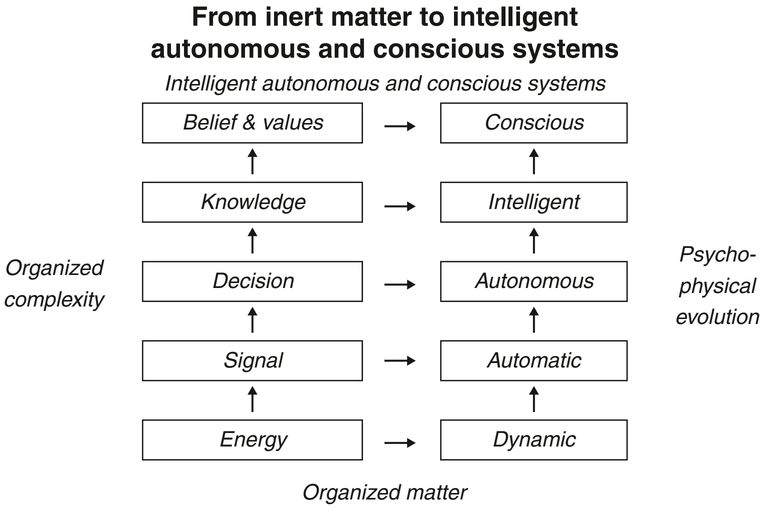

Fig. 1 Tentative scheme of the path leading from inert matter to intelligent autonomous and conscious systems. [13]

duplicate exactly the motion of the arm and hand of a human operator. Later, an increasing number of movements were performed under autonomous control, with the human controller simply taking decisions at a higher level. An analogy is that of the gearbox in a motor car. In basic transmissions the driver has to control the clutch and the gear lever, supplying the power needed to perform the action. In semi-automatic transmissions the driver takes the decision about which gear to engage and the device operates the clutch and the gearbox, using a source of power. In fully automatic gearboxes it is still the driver who controls the speed through the accelerator pedal, and in so doing causes changes of gear. Here all low-level decisions are taken by the device, but the high-level decision is still taken by the driver in real time.

To qualify as a true robot, the device must possess a good degree of autonomy, being able to perform its tasks without direct, real-time, human intervention. A robot must also interact with the environment and perform its tasks in a flexible, easily reprogrammable, way. Thus it belongs to at least the third level in Fig. 1.

Ideally a robot should be even more autonomous from human intervention and should also perform in an intelligent way or even be conscious. Both these characteristics are still far from being present in actual robots.

Speaking about space exploration, an important point is how much autonomy, and thus artificial intelligence, is needed for this task. Generally speaking, it can be stated that the autonomy of robots must increase with the distance from the human controller at which they operate. While it is possible to conceive telemanipulators for all tasks to be performed on the Moon, the autonomy required for Mars exploration (at least until humans are present on that planet or on its satellites) must be of a higher degree. The distance of satellites and planets in the outer Solar System is such that unmanned exploration requires true robots. The distances at which unmanned devices will operate, when interstellar exploration is undertaken, may make it necessary to resort to intelligent machines, in the sense defined above.

Strong AI is based on the assumption that all human characteristics can be duplicated by machines and consequently that they will not only be intelligent, but they will also possess a true mind, with related consciousness. This is, however, an unproved statement and, particularly the last part, quite a controversial one.

A basic assumption in the novel is that the strong AI hypothesis is not supported, not only by the lack of serious evidence, but not even by hints of it. Thus, since thought (and even more, consciousness) is not an algorithmic process, present technology and the technology foreseeable for a medium-term future will not permit the construction of thinking, self-aware machines. None of the robots of the novel could pass the Turing Test, and they are basically machines with an evolved control system but nothing more.

As consequence of the limitations of AI, severe difficulties are encountered in robotic space exploration. As stated above, interplanetary, and above all, interstellar exploration needs highly autonomous robots, able to take decisions without the help of humans. Advances in space travel make human exploration missions increasingly expedient, and the combination of low-cost access to space and efficient space propulsion strongly limits the role of robots in space exploration, except for their use as 'astronaut assistants' or teleoperators in dangerous or difficult places.

Humanoid Robots

Robots are almost a commonplace in science fiction, and the word *robot* was first used by the Czech writer Karel Čapekwho, in 1920, published his science fiction play *R.U.R.* (*Rossum's Universal Robots*), dealing with artificial men built for performing work in place of human beings. He invented the word *Robota*, from the base robot-, as in *robota*, compulsory labor, or *robotník*, peasant owing such labor. (Words that originated in science fiction, such *robot, terraforming* and many others, are now commonly used in the scientific and technological jargon). The robots described in the play are humanoid.

Originally a robot was a sort of 'artificial human', a mechanical slave that had a humanoid body, and sometimes a humanoid behaviour, not to mention the cases in which it also had a humanoid mind. For instance, the definition of *robot* from the *Random House Webster's Dictionary* is "*a machine that resembles a human and does mechanical, routine tasks on command* or *any machine or mechanical device that operates automatically with humanlike skill.*" However, other definitions are wider, and more realistic: the ISO (International Standards Organization) 8373 standard defines a robot as "*an automatically controlled, reprogrammable, multipurpose, manipulator, programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications.*" The ISO definition thus includes industrial robots, which are neither humanoid nor biomorph (nor bio-inspired). However, the robot remains, in the collective imagination, a sort of artificial human, and is the very essence of a bio-inspired machine.

For some applications, mostly when they are designed to work with humans, it may be expedient that the robot actually has a humanoid shape. For instance, a robot that has to move in a structured environment designed for humans may perform better if its overall shape is that of a human being. Other cases are robots built for studying animal or human locomotion or gestural communication: an example of this is Kismet, a research robot built at MIT by Dr. Cynthia Breazeal. It simulates emotion through various facial expressions, vocalizations and movement, and its aim is the study of non verbal communication [14] or those built for the *edutainment* market. Robots working in hospitals, attending to elderly people or children, may be more reassuring if they have a human look. Above all, they may convey messages through their facial expressions and body postures that are immediately and subconsciously understood by people—even people some of whose faculties are impaired, so that the interaction with humans is improved by simulating a humanoid shape and behaviour.

By using a humanoid (or at least animal) means of locomotion (legs instead of wheels), climbing stairs, getting on elevators, going through doors and in general moving in an environment designed for people can be simpler and a humanoid robot can use tools designed for humans: drive vehicles, etc. This is typical of personal robots designed for performing domestic duties: instead of owning a number of household appliances it may be more expedient to own a single service robot (Fig. 2) that can use the same hand tools that were previously directly used by humans.

Apart from the above-mentioned cases, the same functions performed by a humanoid robot may be better performed by a machine whose configuration is directly dictated by its tasks and not by the way nature solved the same problem. A 4-wheeled centauroid robot may be far more suitable to collaborate with humans under many circumstances, both within an unstructured and a structured environment, than its biped counterpart.

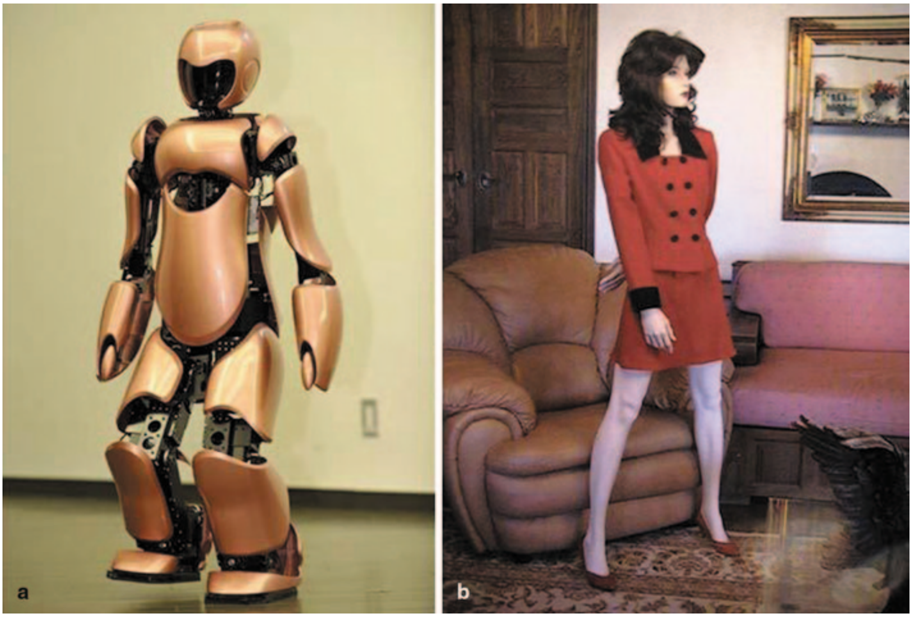

Fig. 2 Domestic robots **a** e-NUVO, a small domestic robot, developed by the Nippon Institute of Technology, with Harada Vehicle Design, ZMP and ZNUG design, (From http://www.plasticpals.com/?*p* = 18810 with kind permission of Prof. Kensuke Takita, NIT, Tokyo). **b** Valerie, anthropomorphic domestic robot presently under development by Android World. This is perhaps closer to the RGs of the novel, although the manufacturers say explicitly it cannot be used in that way. (From http://www.androidworld.com/prod19.htm with kind permission by Chris Willis)

Recent studies (see, among other others [15]) assessed that the market for personal and domestic robots will boom in the first half of the 21st century and some even state that the personal robot industry will have the role that the automotive industry had in the past. However, the performance of the humanoid robots built up to now (the Sony SDR-4X, a small, child size, domestic and entertainment robot, with a vocabulary of 60,000 words, the Honda Asimo work robot, and some others) are still inadequate and they do not yet have a true market.

In the novel, the advances in the field of robotics are not assumed to be particularly fast. Menial tasks are performed by robots that are not necessarily fully humanoid, but have a shape that is adequate for their tasks. These robots have been around for decades, and are certainly not at the cutting edge of technology. At any rate, the place where the novel is set is a space station in a distant, frontier system, so if these robots were costly new technological gadgets, they would not be there.

The only true humanoid robots in the novel are the 'RG', an achronym for robogirls, and their male counterparts. As a character defines them, an RG is "seventy kilos of machinery, moved by electrohydraulic actuators controlled by a computer and covered with silicon flesh and synthetic skin". Their use is the most private type of personal service: sex. On the frontier, where few miners and adventurers take their families with them, their use is, in a way, encouraged to reduce the number of humans doing this job. They mimic human behaviour, at least as far as their programmers succeed in replicating it and, at least from some distance, may be confused with a human being. They too are consolidated technology and are the results of a long development.

At present, many predict that something of this kind will be around by 2020, and there are even predictions that by 2050 they will change completely the market in prostitution [16].

As already stated, most of the technological advances in the novel are assumed to have taken place on a slower timescale than is now predicted. This conservative attitude applies also to details: robots are essentially made with a mechanical body, although the advances in the field of materials allow the construction of stronger and lighter structures, powered by electrohydraulic actuators and controlled by a computer, smaller and much more powerful than present-day ones, even if much less than predictable from Moore's law, but with no revolutionary changes.

These robots in the novel are not intelligent, in the sense that they follow programs, albeit very complex ones, and they are definitely not conscious. At any rate, because they are built to interact with humans and to imitate human behaviour, they are much more complex than other robots, and their computers have the most advanced processing units and memories.

However, the idea that strong AI is viable is still shared by some of the characters who think that, when the complexity of a computer goes beyond a certain threshold, it starts to develop intelligent behaviour. The discussion about intelligent robots is thus brought to a higher, more philosophical (or, rather, theological) level, echoing the 'consciousness-complexity' law from Teilhard de Chardin's theology [17]. A character in the novel states that when a robot is complex enough to reach intelligence and then consciousness, it is endowed with an immortal soul.

Von Neuman Machines

Von Neumann machines are self-replicating robots, although Von Neumann called them Universal Constructors. In the novel they are called replicators: a term introduced by Drexler[2] [18] for artificial self-replicating systems based on conventional large-scale technology and automation. The idea is however

[2] Actually Drexler used the term *clanking replicators*, to distinguish them from self-replicating machines at the micro- or nano-scale, which he called *replicators*.

much older, since non-biological self-replicating systems were imagined in Samuel Butler's article *Darwin Among the Machines* published only a few years after *The Origin of Species* [19].

Since 1980, NASA forwarded the idea of using self-replicating factories to develop lunar and asteroid resources, but their use in space exploration is particularly expedient if interstellar exploration is performed by using slow interstellar spacecraft[3], unable to reach a speed that is a substantial fraction of the speed of light.

Interstellar probes must have an operational autonomy that is close to true intelligence. Provided that replicators endowed with sufficient intelligence can be built and miniaturized enough, they could take command of interstellar probes, guiding them to their targets. At that point all distinctions between the intelligent machine and the probe would fade, and it would be more appropriate to talk of a *Von Neumann probe*.

Once it reaches its target, such a probe could choose a suitable asteroid, a planet with a solid surface or a satellite, land on it and start building a copy of itself. A strategy for space exploration based on them has been proposed by Frank Tipler [20].

A Von Neumann probe could be launched towards a nearby star with a comparatively simple propulsion system. After several hundred years, or even many thousand years, it would reach its destination. The probe would land and start producing other probes, which would then leave that extrasolar system, heading off toward other nearby stars. Once its primary task of continuing the expansion to other star systems had been fulfilled, the probes would begin their scientific tasks, sending reports back to Earth. Eventually, most of our galaxy would be settled by these probes. According to Tipler, a single intelligent species could even begin to explore the whole Universe using Von Neumann probes.

It has been computed that through this strategy, using replicator probes travelling at a speed not higher than 10 % of the speed of light, a galaxy the size of the Milky Way can be explored in as little as half a million years [21].

Such intelligent machines might not just explore, but also reproduce organic life. The question is: how small and lightweight can a Von Neumann probe be? Thanks to rapidly developing nanotechnologies, it might be possible to build a very compact and lightweight self-replicating machine, but in the novel the more common opinion that replicators must be gigantic machines, true self-sufficient factories, is accepted. A comprehensive review—provided with a wide bibliography—about replicators can be found in the book *Kinematic Self-Replicating Machines*, by Freitas and Merkle [22].

[3] The term *slow interstellar travel* usually indicates interstellar travel at a speed lower than 1 % of the speed of light ($v = 0.01$ c).

Even when a Von Neumann machine is built, could we be sure that, after many replications of itself, errors would not creep in? After all, this is one of the mechanisms by which evolution creates new living beings. Will a probe programmed on Earth always perform correctly in the new environments that it will find in other planetary systems? Checking, or even modifying, the programming of the probe by radio from the Earth is possible only for the first few replications. Then the distances in both space and time become so large that everything must be done by the on-board artificial intelligence systems. What might be the outcome of such machines, once they stop behaving exactly as their builders envisaged, owing to random modifications of their genetic code?

In this way small replication errors (mutations) could accumulate and a Darwinian evolution[4] of these machines would occur. Since they are huge and powerful, they could become the Doomsday machines (Berserkers) Stephen Webb mentioned in one of his 50 solutions to the Fermi Paradox [23].

Another, more important point has to be addressed. Assuming that such intelligent machines can be built, is it morally acceptable to do so? Should self-replicating machines fill the Universe? That question has caused fierce arguments. Carl Sagan believed the answer to be no, and he stated that [24]:

> …the prudent policy of any technical civilization must be, with very high reliability, to prevent the construction of interstellar von Neumann machines and to circumscribe severely their domestic use. If we accept Tipler's arguments, the entire universe is endangered by such an invention; controlling and destroying interstellar von Neumann machines is then something to which every civilization—especially the most advanced—would be likely to devote some attention.

Frank Tipler's counter-answer is equally strong. If humankind abdicates that role, it will miss all chances of colonizing, first, nearby stellar systems and then the Universe. Humankind will betray its cosmic duty, and condemn itself to extinction. To quote his words: [20]

> This is a position of fear and ignorance, a definition by exclusion: that which is unlike me is not worthy of existence. A "person" is defined by qualities of mind and soul, not by a particular bodily form.

By Frank Tipler's reasoning, the dissemination throughout the Universe of Von Neumann machines may be considered as another aspect of that evolutionary process which produced humankind and which may in future pro-

[4] The first time replicators were mentioned, by Butler in 1840, they were associated with evolution and were thought to be an application of Darwin's ideas to machines.

duce other intelligent species to take its place. The ultimate evolutionary task of humans would thus be to create intelligent machines, i.e., to move the evolutionary line from beings based on the biology of carbon to beings based on the chemistry of silicon.

Although Von Neumann machines are linked with artificial intelligence, and in their version by Tipler they are truly intelligent and conscious robots, a much less advanced artificial intelligence may be sufficient to build replicators. These less advanced replicators—the only ones that are possible within the assumptions considered in the novel—may be even more dangerous than fully conscious ones, which might, after all, have a system of beliefs and values (Fig. 1) preventing them from destroying all organic life.

In the novel, an alien civilization, in some distant part of the galaxy and lost in the mist of time, tried to explore its nearby systems using replicators, which in time transformed into the above-mentioned Doomsday machines, destroying their builders and any living being they encountered in their expansion in space.

Glossary and Achronyms

AI Artificial intelligence

ANN Artificial neural network

Astronomical Unit Distance unit, precisely equivalent to 149,597,870.7 km (92,955,807.3 mi). It roughly corresponds to the mean Earth–Sun distance.

Apparent Magnitude (of a celestial body) A measure of its brightness as seen by an observer on Earth, adjusted to the value it would have in the absence of any atmosphere. The brighter the object appears, the lower the numerical value of its magnitude. An average naked-eye observer under very good conditions can see a star of magnitude 6.5, while the extreme naked-eye visibility limit is between 7 and 8.

BPP Breakthrough propulsion physics, an advanced research program run by NASA from 1996 to 2002.

Centauroid Robot Robot having 4 legs (or wheels) and provided with a more or less humanoid torso with two manipulatory arms.

Drake Equation An equation, introduced by the radio-astronomer and SETI specialist Frank Drake, yielding the number of extraterrestrial civilizations that can enter in contact with us. The coefficients entered into the equation are highly hypothetical, so that the equation is useful for understanding which parameters govern the phenomenon, but is unable to supply a reliable numerical result.

Exoplanet Planet orbiting a star other than the Sun.

Gravitational (or Tidal) Locking Situation in which a satellite orbits so close to a planet (or a planet close to a star) that, owing to tidal effects, the rotational and the orbital motions become synchronized. As a consequence, the secondary body always has the same hemisphere facing the primary body. (The Moon is gravitationally locked to the Earth).

ICT Information and communications technology.

Light year Distance unit, equivalent to 9.4607×10^{12} km (almost 10 trillion km). It is the distance light travels in one year.

FTL Faster than light. FTL travel is considered to be a violation of physical laws because, as a consequence of Relativity, neither matter nor information can move at a speed higher than the speed of light. However, a deeper understanding of physics seems to suggest some possible mechanisms that might be valid in this respect (*see* warp drive).

Moore's law A law, originally stating that the number of transistors on integrated circuits doubles approximately every two years. It has been formulated in different ways, and is now generally interpreted as a doubling of computer performance every two years.

NERVA Nuclear engine for rocket vehicle application, a highly successful program conducted by the U.S. Atomic energy commission and NASA, which demonstrated the feasibility of thermal nuclear propulsion (NTP). At the end of 1968 the latest NERVA engine, the NRX/XE, was tested on the ground with a total run time of 115 min and met the requirements for a manned Mars mission. The program was canceled in 1972.

Parsec Distance unit, equivalent to 30.857×10^{12} km or 3.26156 light years. It is the distance at which the Sun-Earth distance subtends an angle of 1 arcsec.

Propellantless Propulsion Also called space drive, is a hypothetical way of propelling a spacecraft without ejecting material as takes place with rocket engines.

SETI Search for extra terrestrial intelligence.

Space Elevator A structure attached to the Earth's surface and extending into space allowing people and goods to be carried beyond geostationary orbit without the use of rockets or any other form of atmospheric vehicle. It may be imagined as a cable, extended downwards toward the Earth from a geostationary satellite until it is anchored to the surface. Another cable is extended outwards to balance the weight of the former and another satellite (the outer station) is located at its end. Any object released from the outer station is thus launched towards the outer space. The total length of the cable is about 60,000 to 100,000 km. The cable is stressed well beyond the possibilities of any existing material, but it is believed that the progress in the field of materials (mainly nano-engineered materials like carbon nanotubes) will make space elevators possible in the future.

Terraforming An astro-engineering enterprise aimed at the transformation of the physical and environmental characteristics of the surface of a planet to make it suitable for supporting human life. The term *terraforming*, introduced by Isaac Asimov, has been widely used in science fiction, but now the possibility of terraforming planets, and initially Mars, is seriously considered. Terraforming a planet rises heated ethical arguments, in particular if the planet has any indigenous life that is likely to be destroyed in the process. One of the main points is whether it will ever be possible to be absolutely certain that no indigenous life exists on a planet.

Warp Drive Hypothetical faster than light (FTL) propulsion system. It is thought to be consistent with relativity, since FTL travel occurs not by achieving a speed greater than that of light, but by producing a distortion of the spacetime so that the distance traveled is actually shorter than that existing between the start and end point of the travel. It is much used by science fiction writers (e.g., in Star Trek movies) but is also studied by serious scientists.

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