The Fermi Problem

Simon Goodwin, Mar 2014

The Fermi Problem\(^1\) is the apparent discrepancy between the belief that alien technological civilisations are common, and the lack of evidence for them.

**Alien Technological Civilisations**

The Fermi Problem is concerned with *alien technological civilisations* (ATCs) – not alien life in general. An ATC is a species/group with the technological ability to either make their presence known via signals, or to travel between stars.

Whilst chimps and dolphins might be intelligent, they are not technological. For example, if we remotely discovered a planet with aliens of equivalent intelligence we would not be able to distinguish between dolphins and worms (which I am assuming are not intelligent).

It is an open question if humans are an ATC in the sense we mean. We are clearly a technological civilisation, but do we have the ability to communicate our existence, or to travel between stars?

With relatively little technological or industrial effort (e.g. as a fraction of, say, military spending) we could build radio transmitters capable of advertising our existence. (If we would want to do, or should do, this is another question we will return to later.)

We are currently incapable of travel between stars. It would be possible (just, with the same sort of effort that went into the Apollo programme) to send an unmanned probe to some of the closest stars. What is stopping us is a lack of a strong driver to go – the probe would take hundreds of years, so the scientists and politicians who ran and funded the effort would never see the returns. And it is unclear what those returns would be...

When discussing the Fermi Problem it is assumed that we will (fairly soon) become capable of sending probes to other stars at relatively low-cost and will start to bother because the cost is low.

**Are ATCs common?**

There is a common assumption (especially in the general public, but also in the scientific community) that ATCs are common *in our Galaxy.*

The reasoning (often attempted to be ‘quantified’ in the Drake Equation) goes as follows.

1. There are over 100 billion stars in our Galaxy, and many (most?) of these stars have planets around them.
2. The basic constituents of life (CHON+SP, amino acids etc.) are common.
3. Some of those planets will be solid and have liquid water on (or below) the

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\(^1\)Often called the ‘Fermi Paradox’, but I don’t like this as it isn’t actually a paradox.
surface, plus the basic ingredients for life.

4). Life started so quickly on the Earth it suggests life is easy to make given
the right conditions, so life is common.

5). Once life has started, evolution will drive it to multi-cellular life and then
intelligence.

6). Intelligent life will develop technology.

Therefore ATCs should be common in the Galaxy.

One can argue with many of these points (see the discussions of ‘The Rare
Earth Hypothesis’ and ‘The Drake Equation’). In fact, only points (1) and (2)
are known with some degree of certainty, also (3) is probably a pretty good bet
as well. But (4), (5), and (6) are complete speculation (and include all sorts of
hidden assumptions).

But let us take this argument at face value for now and assume that ATCs
are common in the Galaxy. The Fermi Paradox is then – if ATCs are common,
why do we not see them?

Where are the ATCs?

The usual form of the Fermi Problem assumes that ATCs will travel through-
out our Galaxy and therefore should be here already.

Our Galaxy is a disc (spiral) galaxy roughly 60 000 lyr in diameter, and
a few hundred lyr deep. It contains around 100 billion (probably a few times
more) stars, typically separated by 4 or 5 lyr.

The problem of travelling throughout the Galaxy is twofold. Firstly, how to
get from star-to-star? And then, how to explore 100 billion stars?

A reasonable extrapolation from current technology would suggest that we
could get a spaceship up to a few per cent of the speed of light. Therefore, to
travel the 4 lyr from the Sun to α Centauri would take a few hundred years.

The main problem here is how to make a sustainable, stable, liveable envi-
ronment in a spaceship for a few hundred years? Humans have a very limited
range of conditions in which we can survive, and we need a constant source of
clean water and food, plus an atmosphere that re-generates. Small, enclosed
environments are very difficult to maintain (e.g. the Biosphere experiments in
Arizona) – we discuss this much more in ‘Terraforming’.

If faster than light travel is possible given an advanced enough technology
then travel to other stars is much easier as travel time will be much less. An
alternative postulated technology would be suspended animation or some way
of slowing or stopping time.

Let us ignore possible ‘magical technologies’ and remain grounded in our
current knowledge of science, and reasonable extrapolations from it (should we?
We’ll come back to this a bit later). How could we travel to nearby stars?

The most common idea is to use a smart computer. This could be a true
‘artificial intelligence’, or just a computer smart enough to be able to make de-
cisions and react to changing circumstances (is that different from intelligence?
A question beyond this to try and answer). This computer would not require
the extremely precise and sensitive life support a human would and would also
have an extremely long lifetime, so travel for several hundred years would be fairly simple (a power source and some spares, and the ability to repair itself if needed).

This ‘smart probe’ could travel between stars and explore extrasolar planetary systems. But how could one (or a handful) of probes explore the 100 billion stars in our Galaxy?

The idea of a ‘smart probe’ can be extended to a ‘von Neumann probe’ (vNP). A vNP is a smart probe which not only has the ability to repair itself, but also to make copies of itself. It can reach another star, mine and refine material from comets or asteroids, and build copies of itself. One vNP launched by an ATC could reach the nearest star and build 3 copies of itself, those 3 copies travel out and each builds 3 copies, and so on in $N$ generations we would have $3^N$ vNPs, and in 30 generations we would have many more vNPs than stars in the Galaxy.

The question is then how long it takes for the vNPs to go everywhere in the Galaxy? If we take a travel speed of 1 per cent the speed of light, and assume they spend half of their time travelling and half building copies (500 yrs between stars, 500 yrs building), then it would take 5–10 million years to visit every star in the Galaxy at least once (and many several times, if not thousands of times – we have a lot of vNPs buzzing around the Galaxy).

Timescales are important. To us 5–10 Myr sounds like a long time, but the Galaxy is 10 000 Myr, and so this represents only 0.1 per cent of the age of the Galaxy (equivalent to 1.5 minutes in a day). To put this in more context – the Sun and Earth are around 4 500 Myr old, advanced life has been around on Earth for about 550 Myr (since the Cambrian Explosion), the dinosaurs were wiped-out 65 Myr ago, and modern humans have been around for about 0.2 Myr.

Another possibility is that in the (medium-term?) future ‘enhanced humans’ (or ‘enhanced biologies’ to make it more general) could travel between stars. Increased fusion of humans and computers and machinery could make these ‘enhanced humans’ able to survive greater extremes and live much longer, so radically changing the life support requirements for long voyages. A sea journey of a few months was reasonable to our grandparents, similarly a journey of a few hundred years might seem reasonable to an enhanced human with a lifetime of tens of thousands of years.

So travelling between stars, and visiting every star in the Galaxy is potentially possible for ATCs not too far in advance of us without having to postulate new science (any new science makes this so much easier).

The heart of the Fermi Problem is – given that ATCs could explore the whole Galaxy in 5–10 Myr, where are they? This question has two aspects. Firstly, why do we see no evidence of ATCs having visited the solar system, or being present now in the solar system? Secondly, why do we see no evidence for ATCs elsewhere in the Galaxy – either through deliberate or accidental signals, or evidence for large-scale engineering projects?
Timescales are important here. Science fiction most often shows ATCs which are at a very similar (at most plus or minus a few hundred years) point in their technological development. This is for the good reason that we have to be able to understand the ATCs and their motivations to make a good story. However, the true gap in technology and development between us and any ATC will be millions (maybe even billions) of years.

An important aspect of this is when ATCs will arrive in the solar system. The Earth has had life for at least 3 500 Myr (probably more like 4 000 Myr), but multi-cellular plant and animal life for only about 550 Myr (there were some multi-cellular lifeforms before the Cambrian Explosion, but things like the Edicarian Biota were very simple). So an ATC arriving in the solar system would almost certainly arrive when the Earth only has simple single-celled organisms.

Solutions to the Fermi Problem

Possible solutions to the Fermi problem fall into two broad classes.
1. They do exist, but we do not see them or recognise them as ATCs.
2. They do not exist.

Thoughts on UFOs

It is worth mentioning that quite a lot of people do believe that evidence for ATCs exist with UFO sightings/alien abductions/UFO crashes/alien autopsies etc.

UFOs certainly do exist, in that there are things in the sky which are unidentified by the observer. However, jumping immediately from ‘I do not know what that thing is’ to ‘it must be an alien spaceship’ is something of a wild leap. The vast majority of UFO sightings can be explained as aircraft, weather balloons, astronomical or atmospheric phenomena (Venus is a common ‘UFO’).

The role of memory is important – in particular the ‘re-writing’ of memories post-hoc to fit the mental story. Psychological tests show that memory is often very unreliable, and a person’s memory of an event can evolve with time, removing ‘inconvenient’ elements and adding new ‘facts’. Thus even first-hand accounts by perfectly reasonable people cannot be taken at face-value (they quite possibly believe that their memory of the event is correct even though it is not).

There is no good or hard evidence for alien spaceships having visited the Earth. It is possible that the military or government cover such visits up – conspiracy theories often assume that this is just what governments do, but there is no obvious reason to do this. The most obvious reason for militaries being secretive about things is that being secretive is their job, not that they are covering-up crashed alien spaceships.

So I will assume that there is no evidence for ATCs having visited the solar system and the Earth.

They do exist

Following the line of reasoning presented above we are led to the conclusion that ATCs are common. If they are common, where are they?
The point of vNPs

An ATC would probably use vNPs in one of two ways: exploration or colonisation. (Or to seek-and-destroy, see later.)

In exploration, the vNPs would just travel the Galaxy and report back on what they find. Assuming no new science (e.g. FTL communication or travel), this reporting could take Myrs, but a long-lived civilisation might just be interested in what is out there. A vNP could find an interesting planet with life and monitor it and/or explore it for Myrs or more.

Colonisation could take one of two forms.

‘Active’ colonisation would involve finding suitable planets and introducing the host ATC to it. Planets could be terraformed (more correctly, alienoformed) to make them suitable for the ATC, and then life introduced. Given the problems of transporting living things (life support etc., see above) the vNP would probably ‘make’ new life, with information on the composition and structure of the host ATC it could produce living things once at a suitable planet. If the host ATC was ‘enhanced’ then it travelling with the vNP might be possible, and finding a suitable environment would be much easier.

‘Seeding’ colonisation (deliberate panspermia) would involve travelling the Galaxy seeding suitable worlds with basic life and the leaving it to evolve (maybe ‘assisting’ along the way).

Aliens and life on Earth

We think that all life on Earth has evolved from a single common ancestor at least 3 000 Myr ago. The reason for this is that all life on Earth uses the same amino acids, the same nucleic acids, the same basic biochemical molecules and pathways. We can also trace the evolution of life through the fossil record (directly and indirectly) and form genetic connections between different species and even kingdoms of life.

But this does not have to mean that life was generated spontaneously on Earth. An interesting possibility is that an ATC has intervened in the evolution of life on Earth. This might be by seeding the Earth with life initially (deliberate panspermia) and then leaving it alone to see what happens. Or finding a planet with life and ‘helping’ evolution along at various points (the Cambrian Explosion as an alien intervention?).

However, given no evidence for this idea we have to assume that life and the evolution of life on Earth has proceeded with no alien intervention.

They choose not to make themselves known

Many solutions to the Fermi Problem assume ATCs are common, that they have travelled the Galaxy, they have visited the Earth, but that they choose not to make themselves known to us.

One variant on this is ‘The Galactic Zoo’ which suggests that ATCs are deliberately leaving us alone to develop in isolation. This could be a ‘prime directive’ in which ‘primitive’ cultures are left alone. Or that we are considered too primitive/dangerous to be allowed into the Galactic community (yet). Or that we are in ‘quarantine’ and any attempt to leave our solar system will be stopped. (Science fiction often plays with variations on this theme.)
There are two problems with this solution that are generic problems that always need to be considered.

One is ‘uniformity’ – any solution must apply to all groups in all ATCs. If just one group (nation?) in an ATC decides to go against the consensus, then the solution fails.

The other is timescale – solutions to the Fermi Problem often assume that ATCs are dealing with the Earth as it is now, with a developing technological civilisation. But for most of the life of the Earth there has only been simple life. If an ATC arrived 1 000 Myr ago why would it decide to leave the Earth alone? Why would it not alter the Earth and then colonise it? Or if the ATC decided to leave the Earth alone as it had life, why not colonise another (dead) planet such as Mars or Venus?

They can’t be bothered

One possibility is that ATCs cannot be bothered to explore or colonise the entire Galaxy. Once an ATCs vNPs are thousands of lyr away communicating their information would take a very long time, so why bother? And why colonise planets 1000s of lyr away when there are many much closer to home?

The main argument against this is that if something can be done, it probably will be done. The point of vNPs is that they can self-replicate, so only one ever has to be built. And building it would be cheap as the technology would have to exist for much of the work to be done autonomously. And once one is built, a few Myr later there will be trillions of them with no extra effort required by the original builders. So if just one ATC builds a single vNP the Fermi Problem exists.

Space is big

It might be that vNPs have not reached us yet, or have missed us among the 100 billion stars they are searching.

This isn’t very reasonable. We have estimated that the timescale of searching the entire Galaxy is 10 Myr, only a tiny fraction of the age of the Galaxy. If we assume it takes a few Gyr to make enough heavy elements to make planets with life, and then 5 Gyr to evolve to an ATC (how long it has taken us), there is still at least the last 2 Gyr for ATCs to have emerged in. Even if the exploration time is much longer than we have estimated (lets say 200 Myr), then the fraction of time to explore the Galaxy is still only 10 per cent of that time.

In addition, ATCs will know in advance where it is worth visiting. We can detect planets around other stars, and are close to knowing if a planet has life on it. We must assume that more advanced ATCs will be able to search the Galaxy for interesting (living) planets and will target them. If life is rare, then the Earth would be a very interesting target. If life is common, then there should be an ATC nearby.

They are hiding

Another possibility is that ATCs do not advertise their existence as the Galaxy is a dangerous place. If there are many ATCs they might be competing
for resources and so want to destroy (or at least contain, e.g. a variation on the Galactic Zoo) their competition.

One interesting idea is that some vNPs might be designed to seek-and-destroy other vNPs or emerging civilisations. This might be deliberate, or due to ‘evolution’ as vNPs copy themselves (so-called ‘beserkers’).

An argument often used against this is that ATCs will all be ‘nice and civilised’ and not want to do this. Again, this has the problem of uniformity – just one ATC making seek-and-destroy vNPs would be enough (especially as their numbers grow exponentially). Seek-and-destroy vNPs might be needed to counter active or seeding colonisation vNPs from other ATCs.

A major argument against seek-and-destroy vNPs is that we exist. We have been an emerging ATC (from their point of view) for a few thousand years, and we would be detectable within about 100 lyr from radio emissions (our atmosphere would show the signatures of industrialisation for maybe 200 yrs). Therefore any local seek-and-destroy vNPs should have got here and wiped us out as an emerging threat. Maybe one is on its way?

We don’t recognise them

Even the solar system is a big place. It would be quite possible to ‘hide’ (deliberately, or we just haven’t seen them) many vNPs in the solar system. Maybe the solar system has hundreds of vNPs – hanging-out in the Kuiper Belt building new copies of themselves and monitoring us? Unless a large vNP was very close, or actively attempting to communicate with us, it is quite possible we would miss it.

The ATCs we are considering are (by definition) more technologically advanced than we are, by at least hundreds of years, probably by millions or billions of years. They could be attempting to communicate using technology we do not have, or in a way we do not recognise as communication. I will come back to this at the end when I discuss the ‘singularity’ which I really like as a possible solution.

Communication is not worth it

Our current searches for ATCs rely on looking for deliberate attempts to communicate their existence (SETI, see the Drake Equation discussion).

Closely related to the idea above is that ATCs are attempting to communicate their existence to us from a distance (rather than from a vNP in the solar system), but we do not realise this. Either we do not have the technology to receive the communication, or we do not realise it is a communication.

It would seem more sensible to advertise your existence from a vNP, as signals sent from a homeworld or colony would also advertise its location (and is the Galaxy a dangerous place?).

Another possibility that ATCs do not bother attempting to communicate because it would be pointless. An ATC might be so completely different to us that any communication would be meaningless. Dolphins are closely related to us, and have evolved on the same planet at the same time and we do not understand their (probably very sophisticated) language.
Most attempts at ‘languages’ to communicate with ATCs are based around mathematics – but is it worth passing the value of $\pi$ or $e$ to each other in binary? What would either side learn? For us, we would know that an ATC exists, so we would gain a lot. But the ATC knows we exist and would only serve to advertise its existence (is that a good idea?).

Even if the Galaxy is not a dangerous place, we do not know that for sure. Any attempt to advertise your existence has a risk that something might respond that you don’t know about. Maps of the Galaxy should probably contain ‘here be dragons’ warnings.

**ATCs are very rare**

Maybe ATCs are not very common, maybe there are only two or three in the Galaxy? In which case, surely the chance of meeting them is tiny?

The trouble is that a single ATC only has to produce one vNP and the Fermi Problem starts to be a problem as that lone vNP can replicate exponentially.

Maybe ATCs start, but manage to destroy themselves?

A version of this that was popular in the 50s–80s was that ATCs reach the point they discover nuclear weapons, and then they use them to destroy themselves. We haven’t done this, and post cold-war we don’t look like we will anymore (I grew-up in the 80s when this was a very real fear).

But how else could we destroy ourselves as an ATC? The possibilities are quite frightening.

One thought is through environmental catastrophe. As we discuss (especially in ‘Terraforming’), humans are very fragile and require very specific environmental conditions and very specific needs (clean water, food, warmth etc.). Without these very specific things being available in the right way, humans will die.

It is rather heartless, but our consideration in trying to solve the Fermi Problem is not millions (or even billions) of people dying, but rather the ability of the human race to survive as a technological civilisation that matters. In a broader sense it is not even the human race (as we know it) surviving, but rather getting to the point where we produce a computer civilisation, and then we (as biological lifeforms) do not matter any more. I get back to this point later when discussing the singularity.

So the question is – what could destroy the human race as an ITC? Killing lots of humans is not enough, we would need a catastrophe that would destroy our technological ability. Our technological civilisation is based on the availability of energy and raw materials and enough humans to provide the energy and raw materials and turn them into technological products. As well, we need the ability and infrastructure to sustain the humans doing those jobs (provide clean water, food, sanitation, housing, medicine etc.).

‘External’ environmental catastrophe – an external event so significant it destroys human technological civilisation. This could be an asteroid impact, super-volcano, methane release, or anything that so alters the Earth’s climate that so many humans die and/or so much infrastructure is lost that technological civilisation dies.
‘Internal’ environmental catastrophe – any man-made catastrophe. Obvious examples are nuclear or any major WMD war, global warming and extreme climate change. Other worries include the explosion of nanobots (the ‘grey goo’ catastrophe), the (accidental) release of dangerous man-made diseases/organisms...

An interesting aspect of this is that we are beyond the point at which a technological civilisation could be restarted quickly. Our current civilisation is based on the ready availability of energy and raw materials. In particular, energy is the key to our current civilisation. Most of our energy is produced from fossil fuels (solar energy stored as chemical energy by long-dead plants). Now we have the ability to tap ‘renewable’ (e.g. wind, tidal, hydroelectric) or nuclear power these most often require high levels of technology to make them useful (wind power has been used for millennia for windmills, but our power requirements need it turned into electricity to be useful). Our access to both raw materials and energy is now very dependent on energy – deep access to raw materials or fossil fuels, and then the conversion of raw materials to useful products (e.g. aluminium processing).

The up-shot is that if we loose our ability to produce cheap energy, we lose our ability to access sources of energy and raw materials – they are no longer available by digging with pick axes in the right place.

There are some ‘worries’ about the destruction of the human race which aren’t actually a problem in the context of the Fermi Problem. The creation of artificial intelligences that surpass (and then destroy? – it doesn’t actually matter) humanity is not actually a worry. From the point of view of the Fermi Problem, this supplants a biological humanity, which find it difficult to travel between stars, with a computer-based ATC, for which it would be much easier.

If ATCs do not exist because they are destroyed by some catastrophe then we again have the problem of uniformity. All ATCs must be destroyed by catastrophes, and this must happen before they build their first vNP. If they manage to build one vNP then it can continue to explore and replicate (they might send messages back to a long-dead host ATC, but they will carry on).

They do not exist

An obvious explanation for the lack of evidence for ATCs is that there are no ATCs.

At the start we outlined the general argument for ATCs being common:
1). There are over 100 billion stars in our Galaxy, and many (most?) of these stars have planets around them.
2). The basic constituents of life (CHON+SP, amino acids etc.) are common.
3). Some of those planets will be solid and have liquid water on (or below) the surface, plus the basic ingredients for life.
4). Life started so quickly on the Earth it suggests life is easy to make given the right conditions, so life is common.
5). Once life has started, evolution will drive it to multi-cellular life and then
intelligence.

6). Intelligent life will develop technology.

As we have seen in the course, (1) and (2) are true, and (3) is very probably true. So, if ATCs do not exist then what part of this line of argument is wrong?

**Life is rare**

Maybe life is very rare, maybe biogenesis happens only a handful of times in any Galaxy?

The line of reasoning above in (4) goes ‘Life started so quickly on the Earth it suggests life is easy to make given the right conditions’.

The first problem is what are ‘the right conditions’? Is liquid water plus volcanism plus the basic chemical ingredients enough? Or was there something special about the early Earth? We discuss this more in ‘The Rare Earth Hypothesis’.

The first indisputable evidence of life on Earth is around 2.7 Gyr ago (stromatolites), and there is tentative, but more controversial, evidence dating back 3.5 Gyr (from isotope ratios and unusual abundances). One thing that is clear is that life must have appeared before its first appearance in the fossil record, probably quite a long time before. We discuss this much more in ‘Life and the Early Earth’.

The rapid appearance of life suggests that life is quite easy to make. A highly unlikely occurrence will probably not happen early (see the discussion on ‘The Probability of Life’). With one example of life it is difficult to say much, but this is something we should know something about soon. If we find life on planets around nearby stars then we know life must be common. (Finding life on Mars would only tell us this if that life was clearly different to life on Earth, otherwise we cannot rule out the transfer of life from one planet to the other.)

**Advanced life is rare**

Even if life is common, single-celled organisms will never produce an ATC. For a planet to produce an ATC single-celled organisms must develop the ability to produce multi-cellular complex life, and a lot of it. On Earth this involved developing photosynthesis, nitrogen fixing, eukaryotic cells, cellular differentiation, sexual reproduction, and a host of other abilities.

Maybe evolution will just take life down a path towards complexity and multi-cellularity? But how long does this normally take? On Earth the first truly complex multi-cellular animals and plants appeared about 550 Myr ago in the Cambrian Explosion. That is about 4 Gyr since the formation of the Earth, and 2.5-3.5 Gyr since life first appeared.

Was this fast? Slow? About typical? We have no idea, but it matters. Even if evolution will always drive life towards complexity (and this is by no means obvious), if it usually takes 10–20 Gyr then complex life will be very rare. The main sequence life of the Sun is about 10 Gyr, but the Sun is increasing in luminosity and the Earth will become uninhabitable after about 7–8 Gyr (we’ve got another 2–3 Gyr to go). So the lifetime of the star sets an upper limit on the amount of time available for complex life and ATCs to appear.
There is also the limit of the age of the Universe. The Universe is about 12 Gyr old, the Galaxy about 10 Gyr old. It takes a little time to get the heavy elements required for planets and life, so we’ve probably had a maximum of 8 Gyr in which life has been around (maybe a bit less). So, if 8 Gyr is really quick for complex life to appear then it will be extremely rare. If 8 Gyr is plenty of time, then complex life will be common (on planets that have life, which may or may not be common themselves).

**Intelligent life is rare**

Even if life-bearing planets are common, and most of these have complex life, maybe intelligence is rare?

From our experience on the Earth this seems unlikely. The past few decades have seen huge advances in understanding animal behaviour and intelligence, and lots of animals appear intelligent.

Intelligence is difficult to define, but we’ll assume that it is mainly based around problem-solving and learning. Learning is the ability to acquire new skills, i.e. not innate (pre-programmed) abilities. We breath automatically, but we learn how to read. Also intelligence should involve the ability to problem-solve, i.e. to learn how to achieve a particular goal (chimps using sticks to extract ants from their nests to eat, as opposed to an ant-eater have a pre-made long tongue).

From this sort of definition of intelligence lots of animals are intelligent. The obvious animals are chimps and dolphins, but many other animals show this ability to learn and problem-solve (octopi are really good problem-solvers).

This makes evolutionary sense – if an animal can learn and problem-solve it will be better suited to survive and pass-on its genes, especially in times of trouble when normal food sources might be scarce and new sources must be found.

**Technological civilisations are rare**

On the Earth we are the only technological civilisation. Many other animals might be intelligent, but we are the only ones to have developed technology.

Again, ‘technology’ is a rather difficult thing to define. One way of thinking about technology is based around tool manufacture. That is, producing complex tools to solve a problem. Chimps use lumps of wood to batter each other to death, humans sharpen a piece of flint and tie it to the end of a stick, or make a bow and arrow to kill each other.

More broadly, it could be argued that technology is to do with changing the world around you. Rather than sheltering in a cave, it is building a hut. Rather than gathering or hunting wild food, it is growing food plants nearby, or herding and domesticating food animals.

The combination of changing the world around you to make your life easier and having complex tools available allows a surplus of food, and releases some members of society to specialise in activities not related to day-to-day survival (priests, artisans, scientists).
It could be argued that it is a great mental leap to realise that you can alter
the world around you. That the way things are is not how they have to be.
Why have humans made this mental leap to a technological civilisation when
other (clearly intelligent) animals have not? We do not know, but the answer
is crucial in the Fermi Problem. The Galaxy might be full of living worlds
with complex, intelligent life. But if that life is incapable of building a vNP or
communicating its existence then we would not know it was there.

The singularity
A possible solution to the Fermi problem lies in the scientific and technolog-
ical differences between us and a more advanced ATC.
If we consider the technological advances over the last 200 yrs from our
great-great-great-grandparents to us, we have technologies they could not have
dreamt of (radio, TV, computers, planes, phones etc etc etc.). How much more
advanced are ATCs that are thousands, millions, or even billions of years ahead
of us?
As Arthur C Clarke once said ‘Any sufficiently advanced technology is indis-
tinguishable from magic.’ To the ancient Greeks most of our technology would
be magic. So how much of the technology that future humans will have will be
‘magical’? This does not mean that we do not have that technology, but that
we cannot even imagine that technology could exist.
A good example is electronics. Electronics is the basis for much of our
modern technology, and electronics is based on solid state physics, which in
turn relies on quantum mechanics. Before quantum mechanics was developed
in the 1920s it was impossible to conceive that much of our modern technology
could exist.
Of particular interest to us is the recent increase in computing power. The
largest supercomputers are starting to approach the computing power of the
human brain. Estimates of the human brain’s computing power vary, but around
$10^{18}$ FLOPS (floating point operations per second) seems reasonable. Now, in
the early twenty-teens, the largest supercomputers are at $10^{16}$ FLOPS (% of the
brain). Estimates are that in a decade supercomputers will match the human
brain’s processing power.
It is not important if a computer can simulate a human brain, rather it is the
equivalent levels of capacity that are important. We know that a bio-computer
with a power of about $10^{18}$ FLOPS is capable of intelligent thought, learning,
problem-solving, and can be self-conscious. Is an electronic computer with the
same power capable of the same things?
It is obviously more than just processing power that counts. The human
brain has a complex architecture, specialised regions for processing different
information, storage etc. But is the basic source of human intelligence and con-
sciousness (does that matter?) from the high computing power and complexity
of the human brain? Could a computer of similar power and complexity show
the same types of behaviour?
An interesting aside is that the Turing Test is often quoted as a true test of artificial intelligence. In the Turing Test a person has a conversation via a keyboard with a hidden companion. The test is to see if the person can tell if the hidden companion is another human or a computer. Personally, I do not think that the Turing Test is a test of artificial intelligence. Chimps or dolphins are clearly intelligent, but the human would very quickly tell that they were not communicating with another human being...

Right now it is impossible to know if a computer could ever be a true artificial intelligence. If processing power and complexity are all that is required, then there is no reason to think that a computer could not be intelligent in the truest senses of the word. However, some people argue that biology is a crucial aspect of intelligence and consciousness (again, is consciousness important, or do we just think it is because we are self-conscious?). The argument comes down to ‘substrate dependence’ – does the physical composition of the ‘brain’ play a key role in being able to be intelligent? Is there something fundamental about the biological organisation of neurons, proteins, cells etc. in the human brain that makes it a suitable ‘substrate’ for intelligence that an electronic ‘brain’ could never replicate?

Let us assume (and it is my personal feeling that this is true) that computers can become intelligent (and possibly/probably/by definition (?) self-conscious) if they are complex and powerful enough. We might also consider extreme versions of the ‘enhanced biologies’ discussed above – at what point does a biological being become more a computer (Asimov discussed this in reverse in ‘The Bicentennial Man’)?

This changes quite a lot of what we have been thinking in respect of the Fermi problem. Rather than Alien Technological Civilisations (ATCs), we need to consider Computer-based Alien Technological Civilisations (CATCs).

We have implicitly assumed that the ATCs we are considering are biological in some basically similar way to ourselves (see the discussion on ‘What are Aliens like?’). This means that interstellar travel for the ATC is extremely difficult due to life-support and travel time restrictions – hence the need for vNPs. But what if the vNPs were part of the CATC? Given the speed at which vNPs can replicate, vNPs could be the vast majority of the ‘members’ of a CATC.

But what would a CATC want? At a fundamental level every living thing (and we will count CATCs as living) needs energy, resources to grow/reproduce, and an environment that is suitable for it to find these things and not be damaged. Once we are discussing intelligence we might argue that art, exploration, learning, science, enjoyment are things that will be wanted as well (whatever these might mean to an ATC or CATC).

As a biological ATC our requirements are very strict – energy and resources need to come from drinking water and eating plants and animals, and these in turn need sources of energy and resources. Our environment is very restrictive in terms of the temperature, atmospheric composition, ionising radiation flux, and a host of other things. (Basically we have evolved to be optimised for the Earth as it is now.)
As a CATC the basic needs are the same – energy and resources – but the sources are wider (solar, fusion, nuclear sources of power, mining asteroids or comets for resources), and the detailed requirements of the CATC would be far less restrictive (no atmosphere at all, a wide range of temperatures etc.).

In fact, it is unclear if a CATC would really care very much about planets. Resources are easier to gather from comets and asteroids than mining a differentiated planet. The energy cost of leaving a planet like the Earth is high (getting to escape velocity). And all the things we like about the Earth (stable temperatures and conditions and atmosphere) are of much less importance (if any) to a CATC.

Maybe some planets would be prized for their beauty or interest, but that would not mean having to colonise them, rather just visiting or observing them (especially if visiting would destroy/change a feature of interest, such as a developing biological ATC!).

Indeed, it could be argued that CATCs would want to avoid stars most of the time. Computing ability depends on temperature – the lower the temperature the more computing power is available, and the less thermal noise is present. CATCs could well want to stay in environments at a few K (going less than about 10K requires effort, but nature in Giant Molecular Clouds can get this low, and the Kuiper Belt and Oort Cloud are only at a few 10s K). Maybe they would only venture out to explore?

**Postscript. The Simulation Argument**

A seemingly far-fetched idea is that our Universe is not actually ‘real’ in the sense that we might live in a computer simulation. By this we do not mean that our perceptions are fed to us and what we sense is not the real reality (this is the ‘brain in a jar’ idea beloved of philosophers and the ‘Matrix’ films). But rather, that we *are* a computer simulation.

This idea was first put forward by Nick Bostrom (his original article is very readable). It is based around the vast increases in computing power and the possibility of CATCs we discussed above. In particular, the idea that the human race could evolve (or produce) a post-human CATC in the future.

The simulation argument states that one of the following *must* be true:

1. the human race will never reach a post-human stage;
2. any post-human civilisation will not run simulations of past human civilisations;
3. we are almost certainly living in a computer simulation.

We discussed before about the computing resources available to an advanced civilisation. The human brain has a power of about $10^{18}$ FLOPS (and our sensory input amounts to about $10^8$ bits/s), so to simulate a human brain for 100 years would involve about $10^{27}$ operations. If we wished to simulate, say, 100 billion individuals over several thousand years this would increase to around $10^{40}$ operations.

We would also need to simulate the environment and provide sensory input to the ‘brains’. Only the parts of the environment being interacted with by
any individual (or group) need to be simulated, but maybe this would take the number of operations to $10^{45}$.

Pushing our knowledge of computing to its quantum limits could produce a computer the size of the Earth capable of $10^{42}$ FLOPS – that is a civilisation of 100 billion individuals living for thousand of (simulated) years every few minutes!

So – in the distant future if a post-human civilisation wanted to simulate entire past civilisations they could do one every few minutes on a single computer (albeit one the size of a planet). Therefore we might expect there to be millions of simulated pasts (which seem ‘real’ to their inhabitants), but only one real past. Therefore the chance of our civilisation being the single real past is almost zero. Therefore we are almost certainly living in a computer simulation of the past (or a variant of the past) being run in the distant future.

This argument is mainly about future post-humans simulating their ancestor biological humans (us). This is largely due to the probably difficulties in simulating civilisations of biology different to that of the ancestors. Rather than just simulating a ‘brain’, the whole environment and body would need to be simulated down to the quantum level to model the different biology. Also, the initial conditions for a known biology are simpler (start with a group of early humans in Africa and let it run and see what happens).

This is a conclusion that most people will be uncomfortable with (unsurprisingly). So, how can we invalidate it?

Maybe the human race becomes extinct before becoming post-human? So there are no post-humans to run ancestor simulations - is this an even more disturbing possibility?

Maybe post-humans will not run ancestor simulations? This might be ethical – the conscious beings in the simulations feel pain and suffer, and that would be unethical. This does require all post-humans to adhere to these ethics, or to care about them at all – we tend not to care about the suffering of ants. (An interesting possibility is that suffering/goodness could be rewarded in a computer ‘afterlife’.)

Maybe becoming post-human is impossible? Maybe there is something special about biological brains that makes self-aware, intelligent computers impossible (ie. substrate-dependence)?

Maybe simulating a biological human is far more difficult than we have assumed above? We have considered humans purely from the stand-point of the computing power of the brain, but maybe it is impossible to simulate a biological self-consciousness in a computer even if the computer is self-conscious?