
Can Intelligence Explode?

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Abstract

The technological singularity refers to a hypothetical scenario in which technological advances virtually explode. The most popular scenario is the creation of super-intelligent algorithms that recursively create ever higher intelligences. It took many decades for these ideas to spread from science fiction to popular science magazines and finally to attract the attention of serious philosophers. David Chalmers' (JCS 2010) article is the first comprehensive philosophical analysis of the singularity in a respected philosophy journal. The motivation of my article is to augment Chalmers' and to discuss some issues not addressed by him, in particular what it could mean for intelligence to explode. In this course, I will (have to) provide a more careful treatment of what intelligence actually is, separate speed from intelligence explosion, compare what super-intelligent participants and classical human observers might experience and do, discuss immediate implications for the diversity and value of life, consider possible bounds on intelligence, and contemplate intelligences right at the singularity.

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Keywords

singularity; acceleration; intelligence; evolution; rationality; goal; life; value; virtual; computation; AIXI.

“Within thirty years, we will have the technological means to create superhuman intelligence. Shortly after, the human era will be ended.”

— Vernor Vinge (1993)

1 Introduction

The technological singularity is a hypothetical scenario in which self-accelerating technological advances cause infinite progress in finite time. The most popular scenarios are an intelligence explosion [Goo65] or a speed explosion [Yud96] or a combination of both [Cha10]. This quite plausibly is accompanied by a radically changing society, which will become incomprehensible to us current humans close to and in particular at or beyond the singularity. Still some general aspects may be predictable.

Already the invention of the first four-function mechanical calculator one-and-a-half centuries ago [Tho47] inspired dreams of self-amplifying technology. With the advent of general purpose computers and the field of artificial intelligence half-a-century ago, some mathematicians, such as Stanislaw Ulam [Ula58], I.J. Good [Goo65], Ray Solomonoff [Sol85], and Vernor Vinge [Vin93] engaged in singularity thoughts. But it was only in the last decade that the singularity idea achieved wide-spread popularity. Ray Kurzweil popularized the idea in two books [Kur99, Kur05], and the Internet helped in the formation of an initially small community discussing this idea. There are now annual Singularity Summits approaching a thousand participants per year, and even a Singularity Institute.

The singularity euphoria seems in part to have been triggered by the belief that intelligent machines that possess general intelligence on a human-level or beyond can be built within our life time, but it is hard to tell what is cause and effect. For instance, there is now a new conference series on Artificial General Intelligence (AGI) as well as some whole-brain emulation projects like Blue Brain [dGSGR10, GLA⁺10].

A loosely related set of communities which are increasing in momentum are the “Immortalists” whose goal is to extend the human life-span, ideally indefinitely. Immortality and life-extension organizations are sprouting like mushrooms: e.g. the Immortality and the Extropy Institute, the Humanity+ Association, and the Alcor Life Extension, Acceleration Studies, Life Extension, Maximum Life, and Methusalem Foundations.

There are many different potential paths toward a singularity. Most of them seem to be based on software intelligence on increasingly powerful hardware. Still this leaves many options, the major ones being mind uploading (via brain scan) and subsequent improvement, knowledge-based reasoning and planning software (traditional AI research), artificial agents that learn from experience (the machine learning approach), self-evolving intelligent systems (genetic algorithms and artificial life approach), and the awakening of the Internet (or digital Gaia scenario). Physical and biological limitations likely do not allow singularities based on (non-software) physical brain enhancement technologies such as drugs and genetic engineering.

Although many considerations in this article should be independent of the realized path, I will assume a virtual software society consisting of interacting rational agents whose intelligence is high enough to construct the next generation of more intelligent rational agents. Indeed, one of the goals of the article is to discuss what

(super)intelligence and rationality could mean in this setup. For concreteness, the reader may want envisage an initial virtual world like Second Life that is similar to our current real world and inhabited by human mind uploads.

Much has been written about the singularity and David Chalmers' article [Cha10] covers quite wide ground. I essentially agree with all his statements, analysis, and also share his personal opinions and beliefs. Most of his conclusions I will adopt without repeating his arguments. The motivation of my article is to augment Chalmers' and to discuss some issues not addressed by him, in particular what it could mean for intelligence to explode. This is less obvious than it might appear, and requires a more careful treatment of what intelligence actually is. Chalmers cleverly circumvents a proper discussion or definition of intelligence by arguing (a) there is something like intelligence, (b) there are many cognitive capacities correlated with intelligence, (c) these capacities might explode, therefore (d) intelligence might amplify and explode. While I mostly agree with this analysis, it does not tell us what a society of ultra-intelligent beings might look like. For instance, if a hyper-advanced virtual world looks like random noise for humans watching them from the "outside", what does it mean for intelligence to explode for an outside observer? Conversely, can an explosion actually be felt from the "inside" if everything is sped up uniformly? If neither insiders nor outsiders experience an intelligence explosion, has one actually happened?

The paper is organized as follows: *Section 2* briefly recapitulates the most popular arguments why to expect a singularity and why "the singularity is near" [Kur05], obstacles towards a singularity, and which choices we have. *Section 3* describes how an outside observer who does not participate in the singularity might experience the singularity and the consequences he faces. This will depend on whether the singularity is directed inwards or outwards. *Section 4* investigates what a participant in the singularity will experience, which is quite different from an outsider and depends on details of the virtual society; in particular how resources are distributed. *Section 5* takes a closer look at what actually explodes when computing power is increased without limits in finite real time. While by definition there is a speed explosion, who, if anyone at all, perceives an intelligence explosion/singularity depends on what is sped up. In order to determine whether anyone perceives an intelligence explosion, it is necessary to clarify what intelligence actually is and what super-intelligences might do, which is done in *Section 6*. The considered formal theory of rational intelligence allows investigating a wide range of questions about super-intelligences, in principle rigorously mathematically. *Section 7* elucidates the possibility that intelligence might be upper bounded, and whether this would prevent an intelligence singularity. *Section 8* explains how a society right at the edge of an intelligence singularity might be theoretically studied with current scientific tools. Even when setting up a virtual society in our image, there are likely some immediate differences, e.g. copying and modifying virtual structures, including virtual life, should be very easy. *Section 9* shows that this will have immediate (i.e. way before the singularity) consequences on the diversity and value of life. *Section 10* contains some personal

remarks and *Section 11* draws some conclusions.

I will use the following terminology throughout this article. Some terms are taken over or refined from other authors and some are new:

- comp = computational resources
- singularity = infinite change of an observable quantity in finite time
- intelligence explosion = rapidly increasing intelligence far beyond human level
- intelligence singularity = infinite intelligence in finite time
- speed explosion/singularity = rapid/infinite increase of computational resources
- outsider = biological = non-accelerated real human watching a singularity
- insider = virtual = software intelligence participating in a singularity
- computronium = theoretically best possible computer per unit of matter [Bre65]
- real/true intelligence = what we intuitively would regard as intelligence
- numerical intelligence = numerical measure of intelligence like IQ score
- AI = artificial intelligence (used generically in different ways)
- AGI = artificial general intelligence = general human-level intelligence or beyond.
- super-intelligence = AI+ = super-human intelligence [Cha10]
- hyper-intelligent = AI++ = incomprehensibly more intelligent than humans
- world = virtual world. A popular oxymoron is ‘virtual reality’
- virtual = software simulation in a computer.

I drop the qualifier ‘virtual’ if this does not cause any confusion, e.g. when talking about a human in a world, I mean of course a virtual human.

I will assume a strong/physical form of the Church-Turing thesis that everything in nature can be calculated by a Turing machine, i.e. our world including the human mind and body and our environment are computable [Deu97, RH11]. So in the following I will assume without further argument that all physical processes we desire to virtualize are indeed computational and can be simulated by a sufficiently powerful (theoretical) computer. This assumption simplifies many of the considerations to follow, but is seldom essential, and could be lifted or weakened.

2 Will there be a Singularity

The current generations Y or Z may finally realize the age-old dream of creating systems with human-level intelligence or beyond, which revived the interest in this endeavor. This optimism is based on the belief that in 20–30 years the raw computing power of a single computer will reach that of a human brain and that software will not lag far behind. This prediction is based on extrapolating Moore’s law, now valid for 50 years, which implies that comp doubles every 1.5 years. As long as there is demand for more comp, Moore’s law could continue to hold for many more

decades before computronium is reached. Further, different estimates of the computational capacity of a human brain consistently point towards $10^{15} \dots 10^{16}$ flop/s [Kur05]: Counting of neurons and synapses, extrapolating tiny-brain-part simulations, and comparing the speech recognition capacities of computers to the auditory cortex.

The most compelling argument for the emergence of a singularity is based on Solomonoff's law [Sol85] which Yudkowski [Yud96] succinctly describes as follows:

“If computing speeds double every two years,
what happens when computer-based AIs are doing the research?
Computing speed doubles every two years.
Computing speed doubles every two years of work.
Computing speed doubles every two subjective years of work.
Two years after Artificial Intelligences reach human equivalence, their speed doubles. One year later, their speed doubles again.
Six months - three months - 1.5 months ... Singularity.”

Interestingly, if this argument is valid, then Moore's law in a sense predicts its own break-down; not the usually anticipated slow-down, but an enormous acceleration of progress when measured in physical time.

The above acceleration would indeed not be the first time of an enormous acceleration in growth. The economist Robin Hanson argues that “Dramatic changes in the rate of economic growth have occurred in the past because of some technological advancement. Based on population growth, the economy doubled every 250'000 years from the Paleolithic era until the Neolithic Revolution. This new agricultural economy began to double every 900 years, a remarkable increase. In the current era, beginning with the Industrial Revolution, the worlds economic output doubles every fifteen years, sixty times faster than during the agricultural era.” Given the increasing role of computers in our economy, computers might soon dominate it, locking the economic growth pattern to computing speed, which would lead to a doubling of the economy every two (or more precisely 1.5) years, another 10 fold increase. If the rise of superhuman intelligences causes a similar revolution, argues Hanson [Han08], one could expect the virtual economy to double on a monthly or possibly on a weekly basis. So the technological singularity phenomenon would be the next and possibly last growth acceleration. Ray Kurzweil is a master of producing exponential, double exponential, and singular plots [Kur05], but one has to be wary of data selection, as Juergen Schmidhuber has pointed out.

Chalmers [Cha10] discusses various potential obstacles for a singularity to emerge. He classifies them into structural obstacles (limits in intelligence space, failure to takeoff, diminishing returns, local maxima) and manifestation obstacles (disasters, disinclination, active prevention) and correlation obstacles. For instance, self-destruction or a natural catastrophe might wipe out the human race [BC08].

Also, the laws of physics will likely prevent a singularity in the strict mathematical sense. While some physical theories in isolation allow infinite computation in

finite time (see Zeno machines [Wey27] and hypercomputation [Cop02] in general), modern physics raises severe barriers [Bre65, Bek03, Llo00, Aar05]. But even if so, today's computers are so far away from these limits, that converting our planet into computronium would still result in a vastly different world, which is considered a reasonable approximation to a true singularity. Of course, engineering difficulties and many other obstructions may stop the process well before this point, in which case the end result may not account as a singularity but more as a phase transition à la Hanson or even less spectacular.

Like Chalmers, I also believe that disinclination is the most (but not very) likely defeater of a singularity. In the remainder of this article I will assume absence of any such defeaters, and will only discuss the structural obstacles related to limits in intelligence space later.

The appearance of the first super-intelligences is usually regarded as the ignition of the detonation cord towards the singularity – the point of no return. But it might well be that a singularity is already now unavoidable. Politically it is very difficult (but not impossible) to resist technology or market forces as e.g. the dragging discussions on climate change vividly demonstrate, so it would be similarly difficult to prevent AGI research and even more so to prevent the development of faster computers. Whether we are before, at, or beyond the point of no return is also philosophically intricate as it depends on how much free will one attributes to people and society; like a spaceship close to the event horizon might in principle escape a black hole but is doomed in practice due to limited propulsion.

3 The Singularity from the Outside

Let us first view the singularity from the outside. What will observers who do not participate in it “see”. How will it affect them?

First, the hardware (computers) for increasing comp must be manufactured somehow. As already today, this will be done by (real) machines/robots in factories. Insiders will provide blue-prints to produce better computers and better machines that themselves produce better computers and better machines ad infinitum at an accelerated pace. Later I will explain why insiders desire more comp. Non-accelerated real human (outsiders) will play a diminishing role in this process due to their cognitive and speed limitations. Quickly they will only be able to passively observe some massive but incomprehensible transformation of matter going on.

Imagine an inward explosion, where a fixed amount of matter is transformed into increasingly efficient computers until it becomes computronium. The virtual society like a well-functioning real society will likely evolve and progress, or at least change. Soon the speed of their affairs will make them beyond comprehension for the outsiders. For a while, outsiders may be able to make records and analyze them in slow motion with an increasing lag. Ultimately the outsiders' recording technology will

not be sufficient anymore, but some coarse statistical or thermodynamical properties could still be monitored, which besides other things may indicate an upcoming physical singularity. I doubt that the outsiders will be able to link what is going on with intelligence or a technological singularity anymore.

Insiders may decide to interact with outsiders in slow motion and feed them with pieces of information at the maximal digestible rate, but even with direct brain-computer interfaces, the cognitive capacity of a human brain is bounded and cannot explode. A technologically augmented brain may explode, but what would explode is the increasingly dominant artificial part, rendering the biological brain eventually superfluous — a gradual way of getting sucked into the inside world. For this reason, also intelligence amplification by human-computer interfaces are only temporarily viable before they either break down or the extended human becomes effectively virtual.

After a brief period, intelligent interaction between insiders and outsiders becomes impossible. The inside process may from the outside resemble a black hole watched from a safe distance, and look like another interesting physical, rather than societal, phenomenon.

This non-comprehensibility conclusion can be supported by an information-theoretic argument: The characterization of our society as an information society becomes even better, if not perfect, for a virtual society. There is lots of motivation to compress information (save memory, extract regularities, and others), but it is well-known [LV08] that maximally compressed information is indistinguishable from random noise. Also, if too much information is produced, it may actually “collapse”. Here, I am not referring to the formation of black holes [Bek03], but to the fact that a library that contains all possible books has zero information content (cf. the Library of Babel). Maybe a society of increasing intelligence will become increasingly indistinguishable from noise when viewed from the outside.

Let us now consider outward explosion, where an increasing amount of matter is transformed into computers of fixed efficiency (fixed comp per unit time/space/energy). Outsiders will soon get into resource competition with the expanding computer world, and being inferior to the virtual intelligences, probably only have the option to flee. This might work for a while, but soon the expansion rate of the virtual world should become so large, theoretically only bounded by the speed of light, that escape becomes impossible, ending or converting the outsiders’ existence.

So while an inward explosion is interesting, an outward explosion will be a threat to outsiders. In both cases, outsiders will observe a speedup of cognitive processes and possibly an increase of intelligence up to a certain point. In neither case will outsiders be able to witness a true intelligence singularity.

Historically, mankind was always outward exploring; just in recent times it has become more inward exploring. Now people more and more explore virtual worlds rather than new real worlds. There are two reasons for this. First, virtual worlds can be designed as one sees fit and hence are arguably more interesting, and second,

outward expansion now means deep sea or space, which is an expensive endeavor. Expansion usually follows the way of least resistance.

Currently the technological explosion is both inward and outward (more and faster computers). Their relative speed in the future will depend on external constraints. Inward explosion will stop when computronium is reached. Outward explosion will stop when all accessible convertible matter has been used up (all on earth, or in our galaxy, or in our universe).

4 The Singularity from the Inside

Let us now consider the singularity from the inside. What will a participant experience?

Many things of course will depend on how the virtual world is organized. It is plausible that various characteristics of our current society will be incorporated, at least initially. Our world consists of a very large number of individuals, who possess some autonomy and freedom, and who interact with each other and with their environment in cooperation and in competition over resources and other things. Let us assume a similar setup in a virtual world of intelligent actors. The world might actually be quite close to our real world. Imagine populating already existing virtual worlds like Second Life or World of Warcraft with intelligent agents simulating scans of human brains.

Consider first a world based on fixed computational resources. As indicated, initially, the virtual society might be similar to its real counter-part, if broadly understood. But some things will be easier, such a duplicating (virtual) objects and directed artificial evolution. Other things will be harder or impossible, such as building faster virtual computers and fancier gadgets reliant on them. This will affect how the virtual society will value different things (the value of virtual life and its implications will be discussed later), but I would classify most of this as a change, not unlike in the real world when discovering or running out of some natural resource or adapting to new models of society and politics. Of course, the virtual society, like our real one, will also develop: there will be new inventions, technologies, fashions, interests, art, etc., all virtual, all software, of course, but for the virtuals it will feel real. If virtuals are isolated from the outside world and have knowledge of their underlying computational processes, there would be no quest for a virtual theory of everything [Hut10], since they would already know it. The evolution of this world might include weak singularities in the sense of sudden phase transitions or collapses of the society, but an intelligence explosion with fixed comp, even with algorithmic improvements seems implausible.

Consider now the case of a world with increasing comp. If extra comp is used for speeding up the whole virtual world uniformly, virtuals and their virtual environment alike, the inhabitants would actually not be able to recognize this. If their subjective thought processes will be sped up at the same rate as their surroundings, nothing

would change for them. The only difference, provided virtuals have a window to the outside real world, would be that the outside world slows down. If comp is sped up hyperbolically, the subjectively infinite future of the virtuals would fit into finite real time: For the virtuals, the external universe would get slower and slower and ultimately come to a halt. Also outsiders would appear slower (but not dumber).

This speed-up/slow-down phenomenon is inverse compared to flying into a black hole. An astronaut flying into a black hole will pass the Schwarzschild radius and hit the singularity in finite subjective time. For an outside observer, though, the astronaut gets slower and slower and actually takes infinite time to vanish behind the Schwarzschild radius.

If extra comp is exclusively used to expand the world and add more virtuals, there is no individual speedup, and the bounded individual comp forces intelligence to stay bounded, even with algorithmic improvements. But larger societies can also evolve faster (more inventions per real time unit), and if regarded as a super-organism, there might be an intelligence explosion, but not necessarily so: Ant colonies and bee hives seem more intelligent than their individuals in isolation, but it is not obvious how this scales to unbounded size. Also, there seems to be no clear positive correlation between the number of individuals involved in a decision process and the intelligence of its outcome.

In any case, the virtuals as individuals will not experience an intelligence explosion, even if there was one. The outsiders would observe virtuals speeding up beyond comprehension and would ultimately not recognize any further intelligence explosion.

The scenarios considered in this and the last section are of course only caricatures. An actual world will more likely consist of a wide diversity of intelligences: faster and slower ones, higher and lower ones, and a hierarchy of super-organisms and sub-worlds. The analysis becomes more complicated, but the fundamental conclusion that an intelligence explosion might be unobservable does not change.

5 Speed versus Intelligence Explosion

The comparison of the inside and outside view has revealed that a speed explosion is not necessarily an intelligence explosion. In the extreme case, insiders may not experience anything and outsiders may witness only noise.

Consider an agent interacting with an environment. If both are sped up at the same rate, their behavioral interaction will not change except for speed. If there is no external clock measuring absolute time, there is no net effect at all.

If only the environment is sped up, this has the same effect as slowing down the agent. This does not necessarily make the agent dumber. He will receive more information per action, and can make more informed decisions, provided he is left with enough comp to process the information. Imagine being inhibited by very slowly responding colleagues. If you could speed them up, this would improve your

own throughput, and subjectively this is the same as slowing yourself down. But (how much) can this improve the agent’s intelligence? In the extreme case, assume the agent has instant access to all information, not much unlike we already have by means of the Internet but much faster. Both usually increase the quality of decisions, which might be viewed as an increase in intelligence. But intuitively there should be a limit on how much information a comp-limited agent can usefully process or even search through.

Consider now the converse and speed up the agent (or equivalently slow down the environment). From the agent’s view, he becomes deprived of information, but has now increased capacity to process and think about his observations. He becomes more reflective and cognitive, a key aspect of intelligence, and this should lead to better decisions. But also in this case, although it is much less clear, there might be a limit to how much can be done with a limited amount of information.

The speed-up/slow-down effects might be summarized as follows:

Performance per unit real time:

- Speed of agent positively correlates with cognition and intelligence of decisions
- Speed of environment positively correlates with informed decisions

Performance per subjective unit of agent time from agent’s perspective:

- slow down environment = increases cognition and intelligence but decisions become less informed
- speed up environment = more informed but less reasoned decisions

Performance per environment time from environment perspective:

- speed up agent = more intelligent decisions
- slow down agent = less intelligent decisions

I have argued that more comp, i.e. speeding up hardware, does not necessarily correspond to more intelligence. But then the same could be said of software speedups, i.e. more efficient ways of computing the same function. If two agent algorithms have the same I/O behavior, just one is faster than the other, is the faster one more intelligent?

An interesting related question is whether progress in AI has been mainly due to improved hardware or improved software. If we believe in the former, and we accept that speed is orthogonal to intelligence, and we believe that humans are “truly” intelligent (a lot of ifs), then building AGIs may still be far distant.

As detailed in Section 7, if intelligence is upper-bounded (like playing optimal minimax chess), then past this bound, intelligences can only differ by speed and available information to process. In this case, and if humans are not too far below this upper bound (which seems unlikely), outsiders could, as long as their technology permits, record and play a virtual world in slow motion and be able to grasp what is going on inside.

In this sense, a singularity may be more interesting for outsiders than for insiders. On the other hand, insiders actively “live” potential societal changes, while outsiders only passively observe them.

Of course, more comp only leads to more intelligent decisions if the decision algorithm puts it to good use. Many algorithms in AI are so-called anytime algorithms that indeed produce better results if given more comp. In the limit of infinite comp, in simple and well-defined settings (usually search and planning problems), some algorithms can produce optimal results, but for more realistic complex situations (usually learning problems), they saturate and remain sub-optimal [RN10]. But there is one algorithm, namely AIXI described in Section 7, that is able to make optimal decisions in arbitrary situations given infinite comp.

Together this shows that it is non-trivial to draw a clear boundary between speed and intelligence.

6 What is Intelligence

There have been numerous attempts to define intelligence; see e.g. [LH07a] for a collection of 70+ definitions from the philosophy, psychology, and AI literature, by individual researchers as well as collective attempts.

If/since intelligence is not (just) speed, what is it then? What will super-intelligences actually do?

Historically-biologically, higher intelligence, via some correlated practical cognitive capacity, increased the chance of survival and number of offspring of an individual and the success of a species. At least for primates leading to homo sapiens this was the case until recently. Within the human race, intelligence is now positively correlated with power and/or economic success [Gea07] and actually negatively with number of children [Kan07]. Genetic evolution has been largely replaced by memetic evolution [Daw76], the replication, variation, selection, and spreading of ideas causing cultural evolution.

What activities could be regarded as or are positively correlated with intelligence? Self-preservation? Self-replication? Spreading? Creating faster/better/higher intelligences? Learning as much as possible? Understanding the universe? Maximizing power over men and/or organizations? Transformation of matter (into computronium?)? Maximum self-sufficiency? The search for the meaning of life?

Has intelligence more to do with thinking or is thinking only a tool for acting smartly? Is intelligence something anthropocentric or does it exist objectively? What are the relations between other predicates of human “spirit” like consciousness, emotions, and religious faith to intelligence? Are they part of it or separate characteristics and how are they interlinked?

One might equate intelligence with rationality, but what is rationality? Reasoning, which requires internal logical consistency, is a good start for a characterization but is alone not sufficient as a definition. Indiscriminately producing one true statement after the other without prioritization or ever doing anything with them is not too intelligent (current automated theorem provers can already do this).

It seems hard if not impossible to define rationality without the notion of a goal. If rationality is reasoning towards a goal, then there is no intelligence without goals. This idea dates back at least to Aristotle, if not further; see [LH07b] for details. But what are the goals? Slightly more flexible notions are that of expected utility maximization and cumulative life-time reward maximization [RN10]. But who provides the rewards, and how? For animals, one might try to equate the positive and negative rewards with pleasure and pain, and indeed one can explain a lot of behavior as attempts to maximize rewards/pleasure. Humans seem to exhibit astonishing flexibility in choosing their goals and passions, especially during childhood. Goal-oriented behavior often appears to be at odds with long-term pleasure maximization. Still, the evolved biological goals and desires to survive, procreate, parent, spread, dominate, etc. are seldom disowned.

But who sets the goal for super-intelligences and how? When building AIs or tinkering with our virtual selves, we could try out a lot of different goals, e.g. selected from the list above or others. But ultimately we will lose control, and the AGIs themselves will build further AGIs (if they were motivated to do so) and this will gain its own dynamic. Some aspects of this might be independent of the initial goal structure and predictable. Probably this initial world is a society of cooperating and competing agents. There will be competition over limited (computational) resources, and those virtuals who have the goal to acquire them will naturally be more successful in this endeavor compared to those with different goals. Of course, improving the efficiency of resource use is important too, e.g. optimizing own algorithms, but still, having more resources is advantageous. The successful virtuals will spread (in various ways), the others perish, and soon their society will consist mainly of virtuals whose goal is to compete over resources, where hostility will only be limited if this is in the virtuals' best interest. For instance, current society has replaced war mostly by economic competition, since modern weaponry makes most wars a loss for both sides, while economic competition in most cases benefits the better.

Whatever amount of resources are available, they will (quickly) be used up, and become scarce. So in any world inhabited by multiple individuals, evolutionary and/or economic-like forces will “breed” virtuals with the goal to acquire as much (comp) resources as possible. This world will likely neither be heaven nor hell for the virtuals. They will “like” to fight over resources, and the winners will “enjoy” it, while the losers will “hate” it. In such evolutionary worlds, the ability to survive and replicate is a key trait of intelligence. On the other hand, this is not a sufficient characterization, since e.g. bacteria are quite successful in this endeavor too, but not very intelligent.

Finally, let us consider some alternative (real or virtual) worlds. In the human world, local conflicts and global war is increasingly replaced by economic competition, which might itself be replaced by even more constructive global collaboration, as long as violaters can quickly and effectively (and non-violently?) be eliminated. It is possible that this requires a powerful single (virtual) world government, to give

up individual privacy, and to severely limit individual freedom (cf. ant hills or bee hives). An alternative societal setup that can only produce conforming individuals might only be possible by severely limiting individual's creativity (cf. flock of sheep or school of fish).

Such well-regulated societies might better be viewed as a single organism or collective mind. Or maybe the world is inhabited from the outset by a single individual. Both worlds could look quite different and more peaceful than the traditional ones created by evolution. Intelligence would have to be defined quite differently in such worlds. Many science fiction authors have conceived and extensively written about a plethora of other future, robot, virtual, and alien societies in the last century.

In the following I will only consider worlds shaped by evolutionary pressures as described above.

7 Is Intelligence Unlimited or Bounded

Another important aspect of intelligence is how flexible or adaptive an individual is. Deep blue might be the best chess player on Earth, but is unable to do anything else. On the contrary, higher animals and humans have remarkably broad capacities and can perform well in a wide range of environments.

In [LH07b] intelligence has been defined as the ability to achieve goals in a wide range of environments. It has been argued that this is a very suitable characterization, implicitly capturing most, if not all traits of rational intelligence, such as reasoning, creativity, generalization, pattern recognition, problem solving, memorization, planning, learning, self-preservation, and many others. Furthermore, this definition has been rigorously formalized in mathematical terms. It is non-anthropocentric, wide-range, general, unbiased, fundamental, objective, complete, and universal. It is the most comprehensive formal definition of intelligence so far. It assigns a real number Υ between zero and one to every agent, namely the to-be-expected performance averaged over all environments/problems the agent potentially has to deal with, with an Ockham's razor inspired prior weight for each environment. Furthermore there is a maximally intelligent agent, called AIXI, w.r.t. this measure. The precise formal definitions and details can be found in [LH07b], but do not matter for our purpose. This paper also contains a comprehensive justification and defense of this approach.

The theory suggests that there is a maximally intelligent agent, or in other words, that intelligence is upper bounded (and is actually lower bounded too). At face value, this would make an intelligence explosion impossible.

To motivate this possibility, consider some simple examples. Assume the world consists only of tic-tac-toe games, and the goal is to win or second-best not lose them. The notion of intelligence in this simple world is beyond dispute. Clearly there is an optimal strategy (actually many) and it is impossible to behave more intelligently than this strategy. It is even easy to artificially evolve or learn these

strategies from repeated (self)play [Hoc03, VNH⁺11]. So in this world there clearly will be no intelligence explosion or intelligence singularity, even if there were a speed explosion.

We get a slightly different situation when we replace tic-tac-toe by chess. There is also an optimal way of playing chess, namely minimax tree search to the end of the game, but unlike in tic-tac-toe this strategy is computationally infeasible in our universe. So in theory (i.e. given enough comp) intelligence is upper-bounded in a chess world, while in practice we can get only ever closer but never reach the bound. (Actually there might be enough matter in the universe to build an optimal chess player, but likely not an optimal Go player. In any case it is easy to design a game that is beyond the capacity of our accessible universe, even if completely converted into computronium).

Still, this causes two potential obstacles for an intelligence explosion. First, we are only talking about the speed of algorithms, which I explained before not to equate with intelligence. Second, intelligence is upper bounded by the theoretical optimal chess strategy, which makes an intelligence explosion difficult but not necessarily impossible: Assume the optimal program has intelligence $I = 1$ and at real time $t < 1$ we have access to or evolved a chess program with intelligence t . This approaches 1 in finite time, but doesn't "explode". But if we use the monotone transformation $1/(1 - I)$ to measure intelligence, the chess program at time t has transformed intelligence $1/(1 - t)$ which tends to infinity for $t \rightarrow 1$. While this is a mathematical singularity, it is likely not accompanied by a real intelligence explosion. The original scale seems more plausible in the sense that $t + 0.001$ is just a tiny bit more intelligent than t , and 1 is just 1000 times more intelligent than 0.001 but not infinitely more. Although the world of chess is quite rich, the real world is vastly and possibly unlimitedly richer. In such a more open world, the intelligence scale may be genuinely unbounded, but not necessarily as we will see. It is not easy though to make these arguments rigorous.

Let us return to the real world and intelligent measure Υ upper bounded by $\Upsilon_{max} = \Upsilon(\text{AIXI})$. Since AIXI is incomputable, we can never reach intelligence Υ_{max} in a computational universe, but similarly to the chess example we can get closer and closer. The numerical advance is bounded, and so is possibly the real intelligence increase, hence no intelligence explosion. But it might also be the case that in a highly sophisticated AIXI-close society, one agent beating another by a tiny epsilon on the Υ -scale makes all the difference for survival and/or power and/or other measurable impact like transforming the universe. In many sport contests split seconds determine a win, and the winner takes it all — an admittedly weak analogy.

An interesting question is where humans range on the Υ -scale: is it so low with so much room above that outsiders would effectively experience an intelligence explosion (as far as recognizable), even if intelligence is ultimately upper bounded? Or are we already quite close to the upper bound, so that even AGIs with enormous comp (but comparable I/O limitations) would just be more intelligent but not incomprehensibly so. We tend to believe that we are quite far from Υ , but is

this really so? For instance, what has once been argued to be irrational (i.e. not very intelligent) behavior in the past, can often be regarded as rational w.r.t. the appropriate goal. Maybe we are already near-optimal goal achievers. I doubt this, but cannot rule it out either.

Humans are not faster but more intelligent than dogs, and dogs in turn are more intelligent than worms and not just faster, even if we cannot pinpoint exactly why we are more intelligent: is it our capacity to produce technology or to transform our environment on a large scale or consciousness or domination over all other species? There are no good arguments why humans should be close to the top of the possible biological intelligence scale, and even less so on a world scale. By extrapolation it is plausible that a world of much more intelligent trans-humans or machines is possible. They will likely be able to perform better in an even wider range of environments on an even wider range of problems than humans. Whether this results in anything that deserves the name intelligence explosion is unclear.

8 Singularitarian Intelligences

Consider a world inhabited by competing agents, initialized with human mind-uploads or non-human AGIs, and increasing comp per virtual. Sections 6 and 7 then indicate that evolutionary pressure increases the individuals' intelligence and the world should converge to a society of AIXIs. Alternatively, if we postulate an intelligence singularity and accept that AIXI is the most intelligent agent, we arrive at the same conclusion. More precisely, the society consists of agents that aim at being AIXIs only being constrained by comp. If this is so, the intelligence singularity might be identified with a society of AIXIs, so studying AIXI can tell us something about how a singularity might look like. Since AIXI is completely and formally defined, properties of this society can be studied rigorously mathematically. Here are some questions that could be asked and answered:

Will a pure reward maximizer such as AIXI listen to and trust a teacher? Likely yes. Will it take drugs (i.e. hack the reward system)? Likely no, since cumulative long-term reward would be small (death). Will AIXI replicate itself or procreate? Likely yes, if AIXI believes that clones or descendants are useful for its own goals. Will AIXI commit suicide? Likely yes (no), if AIXI is raised to believe in going to heaven (hell) i.e. maximal (minimal) reward forever. Will sub-AIXIs self-improve? Likely yes, since this helps to increase reward. Will AIXI manipulate or threaten teachers to give more reward? Likely yes. Are pure reward maximizers like AIXI egoists, psychopaths, and/or killers, or will they be friendly (altruism as extended ego(t)ism)? Curiosity killed the cat and maybe AIXI, or is extra reward for curiosity necessary? Immortality can cause laziness. Will AIXI be lazy? Can self-preservation be learned or need (parts of) it be innate. How will AIXIs interact/socialize in general?

For some of these questions, partial and informal discussions and plausible an-

swers are available, and a couple have been rigorously defined, studied and answered, but most of them are open to date [Hut05, Sch07, OR11, RO11, Hut12]. But the AIXI theory has the potential to arrive at definite answers to various questions regarding the social behavior of super-intelligences close to or at an intelligence singularity.

9 Diversity Explosion and the Value of a Virtual Life

As indicated, some things will be harder or impossible in a virtual world (e.g. to discover new physics) but many things should be easier. Unless a global copy protection mechanism is deliberately installed (like e.g. in Second Life) or copyright laws prevent it, copying virtual structures should be as cheap and effortless as it is for software and data today. The only cost is developing the structures in the first place, and the memory to store and the comp to run them. With this comes the possibility of cheap manipulation and experimentation.

It becomes particularly interesting when virtual life itself gets copied and/or modified. Many science fiction stories cover this subject, so I will be brief and selective here. One consequence should be a “virtuan” explosion with life becoming much more diverse. Andy Clarke [Cla09] writes (without particularly referring to virtuals) that “The humans of the next century will be vastly more heterogenous, more varied along physical and cognitive dimensions, than those of the past as we deliberately engineer a new Cambrian explosion of body and mind.” In addition, virtual lives could be simulated in different speeds, with speeders experiencing slower societal progress than laggards. Designed intelligences will fill economic niches. Our current society already relies on specialists with many years of training, so it is natural to go the next step to ease this process with “designer babies”.

Another consequence should be that life becomes less valuable. Our society values life, since life is a valuable commodity and expensive/laborious to replace/produce/raise. We value our own life, since evolution selects only organisms that value their life. Our human moral code mainly mimics this, with cultural differences and some excesses (e.g. suicide attacks on the one side and banning stem cell research on the other).

If life becomes ‘cheap’, motivation to value it will decline. Analogies are abundant: Cheap machines decreased the value of physical labor. Some expert knowledge was replaced by hand-written documents, then printed books, and finally electronic files, where each transition reduced the value of the same information. Digital computers made human computers obsolete. In games, we value our own life and that of our opponents less than real life, not only because a game is a crude approximation to real life, but also because games can be reset and one can be resurrected. Governments will stop paying my salary when they can get the same research output from a digital version of me, essentially for free.

And why not participate in a dangerous fun activity if in the worst case I have to activate a backup copy of myself from yesterday which just missed out this one (anyway not too well-going) day. The belief in immortality can alter behavior drastically.

Of course there will be countless other implications: ethical, political, economical, medical, cultural, humanitarian, religious, in art, warfare, etc. I have singled out the value of life, since I think it will significantly influence other aspects. Much of our society is driven by the fact that we highly value (human/individual) life. If virtual life is/becomes cheap, these drives will ultimately vanish and be replaced by other goals. If AIs can be easily created, the value of an intelligent individual will be much lower than the value of a human life today. So it may be ethically acceptable to freeze, duplicate, slow-down, modify (brain experiments), or even kill (oneself or other) AIs at will, if they are abundant and/or backups are available, just what we are used to doing with software. So laws preventing experimentation with intelligences for moral reasons may not emerge. With so little value assigned to an individual life, maybe it becomes a disposable.

10 Personal Remarks

I have deliberately avoided discussing consciousness for several reasons: David Chalmers is *the* consciousness expert and not me, he has extensively written about it in general and also in the context of the singularity [Cha10], and I essentially agree with his assessments. Personally I believe in the functionalist theory of identity and am confident that (slow and fast) uploading of a human mind preserves identity and consciousness, and indeed that any sufficiently high intelligence, whether real/biological/physical or virtual/silicon/software is conscious, and that consciousness survives changes of substrate: teleportation, duplication, virtualization/scanning, etc. along the lines of [Cha10].

I have also only considered (arguably) plausible scenarios, but not whether these or other futures are desirable. First, there is the problem of how much influence/choice/freedom we actually have in shaping our future in general and the singularity in particular. Can evolutionary forces be beaten? Second, what is desirable is necessarily subjective. Are there any universal values or qualities we want to see or that should survive? What do I mean by we? All humans? Or the dominant species or government at the time the question is asked? Could it be diversity? Or friendly AI [Yud08]? Could the long-term survival of at least one conscious species that appreciates its surrounding universe be a universal value? A discussion of these questions is clearly beyond the scope of this article.

11 Conclusions

Based on the deliberations in this paper, here are my predictions concerning a potential technological singularity, although admittedly they have a speculative character.

- This century may witness a technological explosion of a degree deserving the name singularity.
- The default scenario is a society of interacting intelligent agents in a virtual world, simulated on computers with hyperbolically increasing computational resources.
- This is inevitably accompanied by a speed explosion when measured in physical time units, but not necessarily by an intelligence explosion.
- Participants will not necessarily experience this explosion, since/if they are themselves accelerated at the same pace, but they should enjoy ‘progress’ at a ‘normal’ subjective pace.
- For non-accelerated non-participating conventional humans, after some short period, their limited minds will not be able to perceive the explosion as an intelligence explosion.
- This begs the question in which sense an intelligence explosion has happened. (If a tree falls in a forest and no one is around to hear it, does it make a sound?)
- One way and maybe the only way to make progress in this question is to clarify what intelligence actually is.
- The most suitable notion of intelligence for this purpose seems to be that of universal intelligence, which in principle allows to formalize and theoretically answer a wide range of questions about super-intelligences. Accepting this notion has in particular the following implications:
 - There is a maximally intelligent agent, which appears to imply that intelligence is fundamentally upper bounded, but this is not necessarily so.
 - If the virtual world is inhabited by interacting free agents (rather than a ‘monistic’ world inhabited by a single individual or a tightly controlled society), evolutionary pressures should breed agents of increasing intelligence that compete about computational resources.
 - The end-point of this intelligence evolution/acceleration (whether it deserves the name singularity or not) could be a society of these maximally intelligent individuals.
 - Some aspects of this singularitarian society might be theoretically studied with current scientific tools.
 - Way before the singularity, even when setting up a virtual society in our image, there are likely some immediate differences, for instance that the value of an individual life suddenly drops, with drastic consequences.

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