A Future Brighter than 100 Trillion Suns

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Anything that is theoretically possible will be achieved in practice, no matter what the technical difficulties, if it is desired greatly enough.

Arthur C. Clarke, *Hazards of Prophecy: The Failure of Imagination* [1]

I. INTRODUCTION

The *zeitgeist* is dark, the mindset one of scarcity. Pick your poison, the prophets of doom say: stagnation or environmental disaster. We have only one Earth, and unless we change our ways and drastically reduce our demands on it, we will overcrowd, overheat, pollute and, why not, nuke it and ourselves to oblivion. Maybe we should just get it over with now and let the planet heal without us. Boohoo.

To those who really think that the world would be better off without people, all I can say is: after you. For the rest of us, once the discussion is framed in terms of collective action – what should *we* do? – it is hard to argue rationally against some form of utilitarianism: to the extent that humanity can be thought of as a single subject, its goal should be to maximize

$$☺ = \int_0^\infty dt \sum_{i=1}^{N(t)} h_i(t) \tag{1}$$

where $h_i(t)$ is the ☺ of human number i at time t and $N(t)$ is population at t. The details of $h_i(t)$ are of secondary importance here; much is implied already by the integral and the sum. As we shall see, they can be meaningfully extended far beyond the myopic limits of contemporary concerns.

II. YES, EARTH IS DOOMED

Do the integral and you are reminded that Earth is, in fact, doomed. As the sun ages, its luminosity increases, temperatures rise and the rate at which atmospheric CO_2 is sequestered by carbonate rocks grows. If you think we have a global warming problem now, just wait another billion years (Ga); by then, the oceans will have all but evaporated, CO_2 levels will be too low to sustain photosynthesis, and the biosphere will collapse (yes, the long term problem is too little CO_2, not too much). In 5 Ga, the sun will turn into a red giant and swallow Mercury, Venus, and finally Earth [2].

1 Ga is a long time; a typical species might last $\mathcal{O}(10^{-3})$ Ga. But humanity is not typical, and the term should arguably include descendants who, while technically no longer of the same species, still share characteristic human traits. In this sense, the humanity of 1 Ga A.D. might be able to alter planetary orbits [3]. Be that as it may, if the integral in Eq. (1) is to pick up anything beyond a few Ga from now, we must master space technology. If not to the point of moving Earth, then to the point of leaving it for good.

Fine, you say; we have 1 Ga to do it, get back to me in 500 million years. But this assumes the continuity of technological civilization. Imagine a cataclysm bad enough to usher in the Middle Ages II. It is not obvious that a climb back to where we are now would be feasible. We have been pulling up the ladder behind us; the easily exploited natural resources which enabled the industrial revolution are gone, the still plentiful alternatives only accessible with an advanced infrastructure already in place. Lose that, and our future may be reduced to an agrarian subsistence culture destined to die with Earth's biosphere.

The window to space may only be open once. For how long is anyone's guess.

Do the sum in Eq. (1) and you are reminded that Earth has finite carrying capacity. Estimates vary, but 10^{10} people will do as an order of magnitude. Multiply by 1 Ga, and total remaining capacity is $\mathcal{O}(10^{19})$ human-years. Again, if we want to significantly raise the cap on maximum attainable ☺, we must venture into space. And since we don't know for how long we'll be able to do so, we had better do it as soon as possible.

III. ...AND MARS IS A DEAD END

The mainstream roadmap to space was laid out by von Braun more than 60 years ago: first an orbital station, then a lunar base, then a Mars settlement [4]. Enthusiasm for a lunar base may have waned, but very many [5], famous [6], accomplished [7], wealthy [8][9][10] and admired [11][12][13] people agree: it is time to colonize Mars.

And at first sight, it makes sense. Mars is the closest match to Earth currently within reach. If going to space means going to other planets, it is the obvious first stop.

But at risk of incurring the wrath of Mars fans, I must admit that I am not convinced. A mission to colonize Mars might help reignite popular support for space exploration – or do lasting damage by turning into a nightmare. Even if everything goes to plan, the path to economic sustainability remains unclear. As a warmup, try to find ways for a base on Antarctica to support itself, then add absence of energy sources besides solar, less

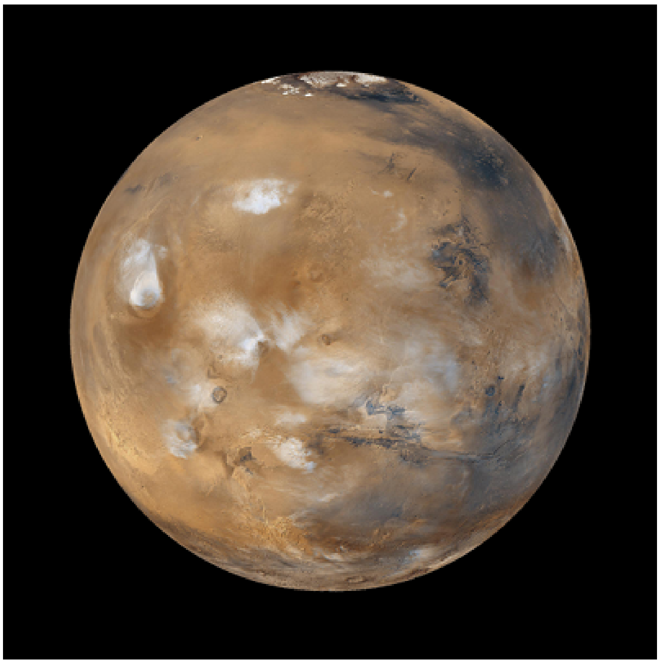

FIG. 1: Mars. Not so hot (NASA).

than half the sunlight, transit times measured in months, the need for pressurized farms, habitats and suits, and the cost of hauling all equipment from Earth. What exactly would a Mars colony export to pay for it all?

Enthusiasts may scoff at such crass concerns, but we have already seen the consequences of ignoring them. Nobody has walked on the moon since 1972. The Apollo program was a stunning success, but once the flag-waving was over, the cost of continued missions became impossible to justify. What will happen to an unsustainable Mars settlement? Do we just leave those who bought one-way tickets to their fate? The ultimate argument for colonizing Mars, that it "backs up" humanity in case of an extinction level event on Earth, only works if the colony can survive unaided.

Even the best-case scenario – that the settlement manages to survive and expand on its own – holds limited appeal. For a long time, growing up on Mars will be like growing up in a sealed refugee camp erected on a frozen desert. How will the first natives feel about that? Will they be haunted by images of an unreachable paradise called Earth?

But let's assume that Mars quickly becomes an enjoyable place to live. Let's even assume that the success story is repeated later, with more advanced technology, on several moons in the outer solar system. The total gain in land area is not even 10-fold, and the quality of that land will not match Earth's. Given 8 Ga of remaining lifetime vs 1 Ga for Earth (without orbital alteration), we are looking at less than a 100-fold improvement in ☺.

We can do much better.

IV. ISLANDS IN THE SKY

The problem here is not the idea of going to space, but the notion that once you manage to climb out of Earth's gravity well, your best option is to immediately plunge into the gravity well of some other space rock. Half a century ago, this might still have qualified as what Clarke called a Failure of Imagination [1]: properly accounting for all known facts, but missing the possibility of yet undiscovered, crucial pieces of the puzzle. Today, it is definitely a Failure of Nerve, the kind of error which occurs when, in Clarke's words, "*even given all the relevant facts* the would-be prophet can not see that they point to an inescapable conclusion".

Already in 1929, J.D. Bernal imagined an air-filled, "spherical shell ten miles or so in diameter", manufactured in space from "the substance of one or more smaller asteroids, rings of Saturn or other planetary detritus" and containing a closed ecosystem, including 20-30 000 people [14]. Four decades later, G.K. O'Neill [15] and friends showed in detail how smaller Bernal spheres, toruses [16] and cylinders could be built using materials mined on the moon and delivered by electromagnetic mass drivers to the stable Lagrangian points of the Earth-Moon system, L_4 and L_5 [17][18].

O'Neill's designs were part of a larger plan emphasizing economic sustainability. New space habitats would pay their way by mining (moon and asteroids), manufacturing (exploiting the high vacuum, microgravity and minimal environmental protection concerns of space) and power generation (beaming solar energy to Earth as microwaves). Unlike planetary settlements, they would be engineered to provide a better quality of life than Earth, and they would initially be close enough to allow significant immigration. Eventually, they could spread throughout the solar system. O'Neill estimated that 3000 times the land area of Earth could be created this way. Less conservative authors put the solar system's carrying capacity at $\mathcal{O}(10^{16})$ people [19][20]. Multiply by $\mathcal{O}(10^{9})$ remaining years of stable energy output from the sun, and you are looking at $\mathcal{O}(10^{25})$ human-years of potential ☺.

So why do we still not have space habitats? Because of upfront costs. Construction of the small Bernal sphere for 10 000 people ("Island One") described in Ch. 8 of [17] was budgeted at 96 bn in 1975 USD (420 bn in 2014 USD, 2.5% of US GDP). O'Neill thought the outlay could be recouped in 24 years, but somebody would still have to make the initial investment. For reference, the final tally for the entire Apollo program, as presented to Congress in 1973, was 25.4 bn.

This could change. The past decade has seen the rise of a new breed of plucky space companies aiming to reduce launch costs (SpaceX, Orbital Sciences, Blue Origin, Stratolaunch, Reaction Engines), open up space to tourists (Virgin Galactic, XCOR), operate commercial space stations (Bigelow Aerospace) and mine asteroids (Planetary Resources, Deep Space Industries). These

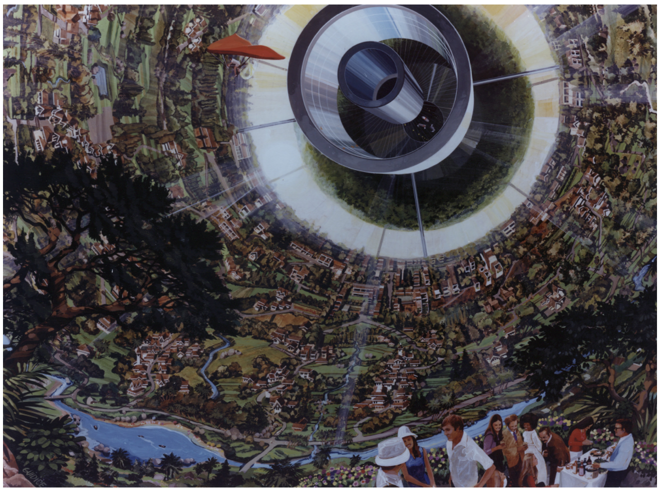

FIG. 2: Inside Island One (NASA).

commercial activities could eventually produce an economically viable path to space habitats. Costs could also be slashed by non-rocket launch systems (mass drivers, launch loops, skyhooks, space elevators...) theoretically capable of reducing prices to orbit by a factor 10 or 100.

But even if O'Neill-style space habitats are never built, the vision of a solar system filled with $\mathcal{O}(10^{16})$ people may prove too timid, for it assumes that humanity itself will remain essentially unchanged.

V. HUMANITY 2.0

Imagine an ordinary-looking server hall. Walking down an aisle, the racks to your left hold the usual assortment of integrated circuits, fiber optics and power cables. The racks to your right hold human brains, each suspended in its own container filled with cerebrospinal fluid, hooked up to a central life support system and connected to a Brain-Computer Interface (BCI). Plumbing for organic materials aside, the brain modules are less demanding than the electronic ones; each one has a modest thermal envelope of 25 W, a 0.5 Gbps data link is plenty for its needs, and it fits in a volume of 5 liters or less (backup life support system included). Yet they don't feel cramped. What they experience is an effectively limitless world. Intellectually, they know that it only exists in the servers across the aisle, but it looks and feels real. Let's call it the Matrix [21].

The advent of the first Matrix seems likely to trail the first manned Mars mission. Virtual worlds are the easy part; we already have those, and they look set for rapid improvement amid growing interest from big technology names (Oculus/Facebook, Sony, Microsoft etc.). The hard technical parts are the BCI and the life support system. Cochlear implants have been around for decades, retinal implants are entering clinical use now [22], implants allowing motor control of artificial limbs are undergoing clinical trials [23]. Development will remain primarily driven by medical and military [24] needs until BCI technology works well enough for ordinary users, maybe several decades from now. Once it's good enough for commercial augmented reality, it will be good enough for the Matrix.

A completely artificial life support system may be the greatest technical hurdle. It is likely to be surmounted gradually, by steady improvements in artificial organs for mainstream surgical use, or possibly sidestepped by genetic engineering; initially at least, the system could be grown rather than built.

Technical difficulties may well play second fiddle to political ones. The first Matrix will emerge through controversy and only gradually, pioneered by individuals with debilitating and incurable medical conditions who first seek solace in existing virtual worlds and then try to escape their bodies. Inevitably, there will be horror stories, calls for regulation and prohibition, and initiatives to evade the same. The latter may involve aging billionaires, countries with authorities amenable to monetary persuasion, and the ultimate extra-jurisdictional frontier: space.

The residents of the Matrix will be superior astronauts. A brain module weighing 1/10 of a Human 1.0 and requiring a shielded volume of 5 liters rather than tens of m^3 is a game changer. You could fit 10 000 of them in 50 m^3, and at less than 100 tons, they could be lifted to low Earth orbit by two Falcon Heavy [25] launches, at a cost of 25 000 USD per person. The Matrix equivalent of O'Neill's Island One might cost a few bn, in the same ballpark as Facebook's bill for Oculus Rift. The location could still be L_4/L_5 or high Earth orbit, with additional material hauled from the asteroid belt to be mined at a convenient distance from Earth. A mixed business model might emerge where you either pay to retire in the new world or sign on for a new life as a prospector, miner, or developer, combining the challenge of space colonization with the attractions of the Matrix.

The moon itself, with only a small molten core, a total volume of $\mathcal{O}(10^{22})$ liters and enough sunlight to power $\mathcal{O}(10^{16})$ brains, could eventually turn into a giant Matrix. The limiting factors would be water and carbon compounds. In the long run, the vast quantities of such materials available in and around the gas giants (notably on Europa and Titan) could shift the balance of humanity to the outer solar system.

As new Matrices crop up further away from Earth, they will strive for independence and organic growth. Incapable of traditional reproduction, they will turn to genetic engineering. Eventually, brains will be born in their artificial "craniums" and with the ability to latch on to their technological extensions unaided. They may also be modified in other ways, e.g. to grow larger. At this point, Humanity 2.0 will be a truly new species – or several, as different Matrices choose mutually incompatible reproductive strategies. Some may go for cloning and pursue an immortality of sorts by passing on per-

FIG. 3: Anything you can imagine. A valkyrie rides an Anubis dragon over Isle of Wyrms in Second Life [26].

sonal memories through their BCIs. Others may stick to tradition and require partners who contribute their genes to a new individual to also act as parents (and, presumably, lay off the dragon avatars while baby is looking; the development and control of children's avatars could be lasting points of contention). Others yet may choose to make the production of new individuals a societal function, with genes sampled from the entire population and socialization of "noobs" a common responsibility.

VI. MATRIX POLITICS

Life in the Matrix could be literally anything you imagine. You've caught glimpses of it in movies and early virtual worlds like Second Life [26]. Want to live in luxury? A fairy-tale castle need not cost more to simulate than a shack in Caracas' slum. Want to be young, fit, beautiful, tall, breathe water, fly, grow a fur, be a dragon? No problem. The Matrix will be an unbeatable playground for all kinds of social, artistic and theoretical endeavors. There will be time, too; with accidents and ailments of the physical body gone, life will last as long as the genetics of brain cells will let it, maybe centuries.

It could also be the ultimate nightmare: with every single bit of data entering and leaving your mind potentially subject to monitoring and manipulation, it is all too easy to imagine the Matrix as the perfect police state or Dante's Inferno. Most ordinary crimes would be pointless in a world where physical safety and material gain have ceased to be issues, but evil, fanaticism and madness require no ulterior motive. How to ensure the integrity of every individual's data link may be the most important political question in the Matrix.

A closely related issue will be access to the real world. Technically, it amounts to remotely controlling a physical avatar rather than a simulated one. The difficulties will be political and economic. Physical avatars will be expensive, limited in number and may require special training to use, if only because natives of the Matrix will be unaccustomed to the real world and would normally think nothing of exposing their "bodies" to destructive conditions. Physical access will also confer great power; even murder becomes an option if you can walk into a data center.

Contemporary analogies which come to mind are professions like fighter pilot and surgeon. Social structures resembling theirs will form. Organizations dealing with the real world will recruit new members by presenting their (mostly quite mundane) activities as the preserve of a special elite, and strive to maintain their status by restricting membership. Maybe prestige and access to advanced robot bodies will be seen as sufficient remuneration, but the cornucopia of the Matrix could be crimped by such "elites" turning into rent-seekers.

The best hope for keeping at least parts of virtual reality from devolving into an aristocracy is the finite speed of light. Latency, the delay between initiating an action and sensing its effect, becomes noticeable to most people above 140 ms. In particularly sensitive contexts, like musicians playing together, the limit is 20 ms, corresponding to a round-trip distance of 6000 km. The physical size of a convincingly realistic Matrix will therefore never much exceed that of Earth's moon. There will be many Matrices, each with its own governance. It may well be possible to "call into" other worlds than one's own as a

FIG. 4: Daedalus standing next to a Saturn V. Image courtesy of Adrian Mann.

virtual visitor, but it will not be the same as truly local presence.

This may cause concepts of society and mind to diverge. BCIs which allow mental states to be shared could eventually cause some Matrices to turn into the hive minds envisioned already by Bernal [14]. If they retain some semblance of humor, they might call themselves "The Borg" [27]. Herein lies a danger; it is not obvious that such hive minds would be sympathetic to unassimilated ones.

VII. ON TO THE GALAXY

A few centuries into this scenario, the solar system is teeming with life. Humans 1.0, increasingly interconnected through BCIs, dominate Earth and maybe Mars. 2.0s enjoy long lives of virtual plenty on the moon, in the asteroid belt, around the gas giants, and maybe on parts of Earth too inhospitable for 1.0s (arctic caps and oceanic methane hydrate deposits come to mind). A conservative estimate based on an individual biomass ratio 5:75 (1.5 kg brain + 3.5 kg life support system vs 75 kg Human 1.0) suggests that carrying capacity is at least a factor 15 larger for 2.0s than 1.0s, allowing a total population of $\mathcal{O}(10^{17})$. And we haven't even left the solar system yet!

But as the good spots fill up, a few trillion brains are sure to be thinking about the $\mathcal{O}(10^{11})$ stars in the Milky Way and their potential population of $\mathcal{O}(10^{28})$. With up to 10 000 Ga of efficient star formation left [28], compared to the sun's remaining lifetime of less than 10 Ga, colonizing the galaxy is worth a ☺ factor $\mathcal{O}(10^{31})$ or more.

It won't be easy. The current gold standard of interstellar engineering, Project Daedalus [29] (soon to be superseded by Project Icarus [30]) would need half a century and 50 000 tons of miniature fusion bombs to deliver a 450 ton flyby probe to Barnard's star, 6 ly away, at an estimated cost of 10^5 bn in 1978 USD (360 trillion in 2014 USD). The world economy would have to grow 50-fold to finance it over a decade at 1% of gross annual product.

This is the kind of effort required to reach even the nearest stars within a Human 1.0's lifetime. Alternatively, you could combine a Daedalus engine with an O'Neill habitat to get a multi-generation ship going at 1-2% of light-speed, for travel times of $\mathcal{O}(10^3)$ years to the nearest stars [31]. Starting from a population of $\mathcal{O}(10^4)$ people [32], such a ship could colonize a new planet system, build more ships, and repeat. 1.0s could spread across the galaxy this way. But chances are that they would be engaging in a losing race.

As in the solar system, Humans 2.0 will be greatly advantaged by their smaller size and greater adaptability. Daedalus could carry the 2.0 equivalent of an Island One at full speed, and its passengers would thrive across a wider range of destinations than their ancestors. Any 1.0 multi-generation ships would quickly be engulfed by a sphere of 2.0-settled territory expanding faster than they can travel.

But even Humans 2.0 might be outrun by their descendants.

VIII. HUMANITY 3.0?

As I write this, Henry Markram and collaborators are working towards the first biologically accurate, cellular-level simulation of a complete rat brain, 10^8 neurons [34]. In a couple of years, they hope to have it running well enough to control a robot rat body. Improving capacity 1000-fold would allow a human brain to be simulated. The DEEP supercomputer currently under development [35] might enable such simulations by the 2020s.

Assuming, as most workers in artificial intelligence and neuroscience seem content to do, that the mind is completely encoded by the connectome and does not depend on deeper physical (or supernatural) properties of the brain, this suggests the possibility of entirely non-biological humans within a decade or two. Let's call them Humans 3.0. How would they compare to 2.0s?

The answer depends largely on the future of computing. Naive extrapolations of "Moore's law", the observation from 1965 that the transistor density of integrated circuits doubles every 18-24 months [36], have led to prophecies of an impending "Singularity" by the year 2050. The idea is that ever-improving hardware will eventually make simulated minds faster than biological ones, and that this speed advantage will be used to create even faster hardware and minds. The resulting exponential "intelligence explosion" would make all prediction beyond this point arduous at best, but messianic visions of material abundance and virtual immortality through mind-uploading are common.

There are many problems with this view. Faster does not necessarily imply smarter; 1000 years as the village idiot do not equal one year as Einstein. Nor is it clear what would motivate a sufficiently intelligent simulated mind to design a superior successor, given the likely "rewards" of obsolescence (self-improvement might be possible, or not). But the most immediate concern is that Moore's law is ending. In terms of cost per transistor, we are already flat-lining; the currently popular 28 nm manufacturing process may well be optimal. A couple more process shrinks will bring further performance gains, with 7-5 nm gates expected by 2020. Absent revolutionary new technologies, finite atom size will then impose a much slower trajectory of primarily design-driven improvements, expected to yield a 30-fold performance gain over the next 50 years [37].

The IBM Blue Gene/P used by Markram *et al.* runs at 56 teraflop/s and simulates a rat's cortical column (10 000 neurons) at 1/300 of real time. Simulation time is proportional to neuron count. As of November 2013, the world's fastest computer, the Tianhe-2, ran at 34 petaflop/s [38], enough to simulate 20 000 neurons in real time. A human brain is five million times larger. Clearly, a 30-fold speedup falls far short of making Humans 3.0 viable.

The proposed solution is neuromorphic computing [39]. Current simulations spend most of their time stepping through thousands of coupled differential equations per cell [40]. Hardware designed specifically to emulate neurons can do much better. A brain cell propagates signals at 100 m/s and can fire $\mathcal{O}(100)$ times/s; electronic circuits propagate signals at near light-speed and can, if clocked, run at GHz rates. This suggests potential speedup factors ranging from 10^6 to 10^{12}. Multiple initiatives, academic [41][42], military [43] and commercial (IBM, Intel *et al.*), are now exploring this approach. The goal is both faster brain emulations and more efficient general purpose computers.

If this program succeeds, it could allow a smooth transition from Humans 2.0 to 3.0. Neuromorphic circuits would gradually replace biological ones, and computers with brain-inspired architectures would run virtual worlds at matching speeds. But interactions with the physical world would have to be rethought.

The reason is elementary mechanics. A human mind which works 10^6 times faster needs a body which moves 10^6 times faster. Acceleration and kinetic energy density are inversely proportional to time scale squared, so a matching physical body would be ripped apart by 10^{12} times larger accelerations and energy densities. Shrinking helps, but the needed factor 10^{-6} would yield bacterium-sized avatars. Realistically, the electronic mind would have to be massively underclocked. It could retain the ability to "freeze" external time at will, e.g. while thinking through a problem or communicating directly with others of its kind, but its body would then be frozen too.

If general purpose computers fail to keep up with minds running on neuromorphic hardware, there will be an analogous problem in virtual worlds. This might lead to a preference for abstract environments stripped of all resemblance to real ones, and encourage self-exploration and modifications inconceivable even to Humans 2.0. As impractical vestiges of the body are purged from the mind, the connection to humanity's roots will grow tenuous.

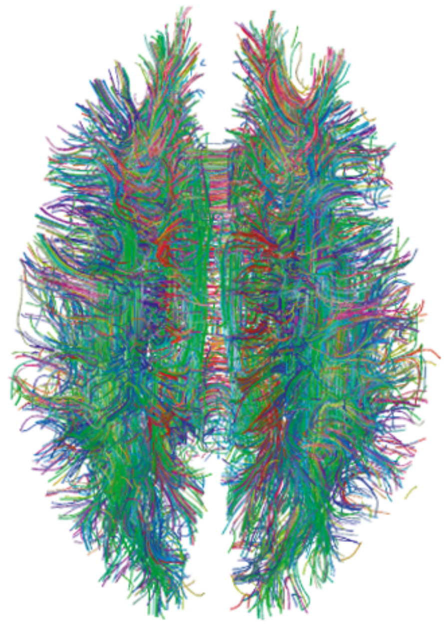

FIG. 5: The connectome [33].

Incidentally, this suggests a simple answer to Bostroms's simulation argument [44]: if the electronic minds of the future find virtual worlds too slow to be attractive, we are unlikely to live in a simulation, without any implication of impending doom.

Whether still living in skeuomorphic virtual worlds or not, Humans 3.0 could boost ☺ by a subjective time factor $\mathcal{O}(10^{12})$, and 1000-fold or more by their population. With all biological components finally gone, they would no longer be limited by water and carbon compounds, and would thrive in an even wider range of physical environments than their predecessors. Unlike 2.0s, they could adapt to irregular power availability by dynamically up- and down-clocking themselves, and might not even balk at hibernating for a few Ga, long enough to venture beyond the $\mathcal{O}(10^{12})$ stars in the Local Galactic Group. Subjectively, such journeys would only last a moment, and (assuming that accelerated cosmological expansion remains the consensus view) may also be motivated by the prospect of losing access to most of the $\mathcal{O}(10^{14})$ stars in the Local Supercluster some 100 Ga from now.

IX. CONCLUSION

Overwhelming as this outlook may seem, we really haven't peered all that far ahead. The technological evolution from us to Humans 3.0 might take a few centuries, a negligible timespan compared to another Ga of life on Earth, 10 000 more Ga of efficient star formation, and 10^{20} Ga of stellar remnants conceivably capable of supporting computation, hence intelligence. I choose to stop here not because we have reached the end of the story – we are barely into Chapter 1 – but because I see little point in trying to guess what 10^{31} virtually immortal minds thinking 10^{12} times faster than me might do next.

What we Humans 1.0 can meaningfully do here and now is focus on writing our own part of the story. In order of priority, we should:

- Reduce the cost of access to space. Non-rocket technologies like space elevators would benefit greatly from stronger materials; solid state physicists have an obvious role to play here.

- Develop fully immersive BCIs. This is a cross-disciplinary problem at the intersection between neuroscience, electronics, software engineering and more.

- Learn how to genetically engineer and grow replacement organs *in vitro*. Even better, develop artificial organs capable of permanently replacing natural ones.

- Build fusion reactors that work. Nothing less will do for interstellar travel.

- Keep exploring new computing technologies. Both computer scientists and physicists are needed; we are nowhere near the ultimate physical limits of computation [45].

If we can tick off all items on this list, Earth will be a better place, and we will be well on our way to the stars.

FIG. 6: Into the Whirlpool. M51, one of $\mathcal{O}(10^4)$ galaxies in the Local Supercluster (NASA).

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