So You Want To Colonize The Universe

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Epistemic Status: Mix of facts, far-future-speculation with the inevitable biases from only considering techniques we know are physically possible, fermi calculations, and an actual spacecraft design made during a one-week research bender.

(this is a sequence. 2, 3, 4, 5)

Part 1a: Gotta Go Fast, Astronomy is a-Wasting

Once a civilization or agent grows up enough to set it sights on colonizing realms beyond its host planet as its first priority (instead of averting existential risks), there is a very strong convergent instrumental goal which kicks in. Namely, going as close to lightspeed (abbreviated as c) as possible.

This is because the universe is expanding, so there is a finite sphere of reachable galaxies, and more pass outside the horizon every year. IIRC (60% probability), about half of the galaxies in the Hubble Ultra-Deep Field are unreachable even if we traveled at lightspeed.

Arriving at a galaxy even one year faster nets you a marginal gain of (one galaxy of stars)*(average stellar luminosity)*(1 year) of energy, which for our Milky way comes out to about 1.6×10^{44} Joules. Assuming energy production on earth stays constant, that's enough energy for a billion years of earth civilization, 130 trillion times over. And I'd expect a transhuman civilization to be quite a few orders of magnitude better at getting value from a joule of energy than our current civilization. And that's just for a single galaxy. There are a lot of galaxies, a one-year speedup in reaching them has tremendous value.

This is basically Bostrom's astronomical waste argument, except Bostrom's version then goes on to apply this loss in total form (which is far larger) instead of marginal form, to argue for the value of reducing existential risk.

Now, there are a few corrections to this to take into account. The first and most important is that, by the Landauer limit, the amount of (irreversible) computations that can be done is inversely proportional to temperature, so waiting until the universe cools down from its current 2.7 K temperature nets you several orders of magnitude more computational power from a given unit of energy than spending it now. Also, if you do reversible computation, this limit doesn't apply except to bit erasures, which nets you a whole lot more orders of magnitude of computation.

Another correction is that if there are aliens, they'll be rushing to colonize the universe, so the total volume a civilization can grab is going to be much smaller than the entire universe. There's still an incentive to go fast to capture more stars before they do, though.

There's also a correction where the total energy available from colonizing at all is more like the mass-energy of a galaxy than the fusion power of a galaxy, for reasons I'll get to in a bit. The marginal loss from tarrying for one year is about the same, though.

And finally, if we consider the case where there aren't aliens and we're going up to the cosmological horizon, the marginal loss is less than stated for very distant galaxies, because by the time you get to a distant galaxy, it will have burned down to red dwarfs only, which aren't very luminous.

Putting all this together, we get the conclusion that, for any agent whose utility function scales with the amount of computations done, the convergent strategy is "go really really fast, capture as many galaxies as possible, store as much mass-energy as possible in a stable form and ensure competitors don't arise, then wait until the universe is cold and dead to run ultra-low-temperature reversible computing nodes."

Part 1b: Stars For the Black Hole God! Utils For the Util Throne!

Now, banking mass-energy for sextillions of years in a way that doesn't decay is a key part of this, and fortunately, there's something in nature that does it! Kerr black holes are spinning rapidly, and warp space around them in such a way that it's possible to recover some energy from them, at the cost of spinning down the black hole slightly. For a maximally spinning black hole, 29% of the mass-energy can be recovered as energy via either the Penrose Process (throwing something near the hole in a way that involves it coming back with more energy than it went in), or the Blandford-Znajek Process (which involves setting up a magnetic field around the hole and this inducing a current, and this is a major process powering quasars). I'm more partial to the second because it produces a current. Most black holes are Kerr black holes, and we've found quite a few black holes (including supermassive ones) that are spinning at around 0.9x the maximum spin, so an awful lot of energy can be extracted from them. So, if we sacrificed the entire Milky Way galaxy to the black hole at the center by nudging stellar orbits until they all went in, we'd have 5x10^57 joules of extractible energy to play around with. Take a minute to appreciate how big this is. And remember, this is per-galaxy. Another order of magnitude could be gotten if there's some way for a far-future civilization to interface with dark matter.

So, the dominant strategy is something like "get to as much of the universe as fast as possible, and sacrifice all the stars you encounter to the black hole gods, and then in the far far future you can get the party started, with an absolutely ridiculous amount of energy at your disposal, and also the ability to use a given unit of energy far far more efficiently than we can today, by reversible computation and the universe being really cold"

(It's a fuzzy memory, and Eliezer is welcome to correct me on this if I've misrepresented his views, and I'll edit this section)

Due to the expansion of the universe, these mega-black-holes will be permanently isolated from each other. I *think* Eliezer's proposal was to throw as much mass back to the Milky Way as possible, and set up shop there, instead of cutting far-future civilization into a bunch of absolutely disconnected islands. I don't think this is as good, because I'd prefer a larger civilization over the whole universe (from not having to throw mass back to the milky way, just throw it to the nearest hole), cut into more disconnected islands, than a much smaller civilization that's all in one island.

Part 1c: The Triple Tradeoff

In unrelated news, there's also a unsettling argument that I came up with that there's a convergent incentive to reduce the computational resources the computing node consumes. If you switch a simulated world to be lower fidelity, and 80% as fun, but now it only takes a fifth of the computational resources so 5x as much lifespan is available, I think I'd take that bargain. Taking this to the endpoint, I made the joke on a Dank EA Memes poll that the trillion trillion heavens of the far-future all have shitty Minecraft graphics, but I'm actually quite uncertain how that ends up, and there's also the argument that most of the computational power goes to running the minds themselves and not the environment, in which case there's an incentive for simplifying one's own thought processes so they take less resources.

Generalizing this, there seems to be a three-way tradeoff between population, lifespan, and computational resources consumed per member. Picking the population extreme, you'd get a gigantic population of short-lived simple agents. Picking the lifespan extreme, you get a small population of simple agents living for a really really long time. Picking the computational resources extreme, you get a small population of short-lived really really posthuman agents. (note that short-lived can still be quite long relative to human lifespans) I'm not sure what the best tradeoff point is here, and it may vary by person, so something like "you get a finite but ridiculously large amount of computational resources, and if you want to be simpler and live longer, or go towards ever-greater heights of posthumanity with a shorter life, or have a bunch of babies and split your resources with them, you can do that". However, that approach plus would lead to most of the population being descended from people who valued reproduction over long life or being really transhuman, and they'd get less resources for themselves, and that seems intuitively bad. Also maybe there could be merging of people, with associated pooling of resources? I'm not quite sure how to navigate this tradeoff, except to say that the population extreme of it seems bad, and that it's a really important far-future issue. I should probably also point out that if this is the favored approach, in the long-time limit, most of those that are left will be those that have favored lifespan over being really transhuman or reproduction, so I guess the last thing left living before heat death *might* actually be a minimally-resource-intensive conscious agent in a world with low-quality graphics.

Part 1d: An Exploitable Fiction Opportunity

Also, in unrelated news, I think I see an exploitable gap in fiction-writing. The elephant in the room for all space-travel stories is that space is incompatible with mammals, and due to advances in electronics, it just makes more sense to send up robotic probes.

However, Burnside's Zeroth Law of Space Combat is:

> Science fiction fans relate more to human beings than to silicon chips.

I'm not a writer, but this doesn't strike me as entirely true, due to the tendency of humans to anthropomorphize. When talking about the goal of space travel being to hit up as many stars and galaxies as possible as fast as possible, and throw them into black holes, the *very first thing* that came to mind was "aww, the civilization is acting just like an obsessive speedrunner!"

I like watching speedruns, it's absolutely fascinating watching that much optimization power being directed at the task of going as fast as possible in defiance of the local rules and finding cool exploits. I'd totally read about the exploits of a civilization that's overjoyed to find a way to make their dust shields 5% more efficient because that means they can reach a few thousand more galaxies, and Vinny the Von Neumann probe struggling to be as useful as it can given that it was sent to a low-quality asteroid, and stuff like that. The stakes are massive, you just need to put in some work to make the marginal gain of accelerated colonization more vivid for the reader.

It's the ultimate real-life tale of munchkinry for massive stakes and there's also ample "I know you know I know..." reasoning introduced by virtue of light-speed communication delays, and everyone's on the same side vs. nature.

I think Burnside might have been referring to science fiction for a more conventional audience, given the gap between his advice and my own reaction. But hard-sci-fi fans are already a pretty self-selected group, and Less Wrong readers are even moreso, and besides, with the advent of the internet, really niche fiction is a lot easier to pull off, it feels like there's a Hard-SciFi x Speedrunning niche out there available to be filled. A dash of anthropomorphization along with Sufficiently Intelligent Probes feels like it could go a long way towards making people relate to the silicon chips.

So I think there's an exploitable niche here.

Putting all this to the side, though, I'm interested in the "go fast" part. Really, how close to light speed is attainable?

So You Want to Colonize the Universe Part 2: Deep Time Engineering

Part 2: Deep Time Engineering

(1, 3, 4, 5)

So, with "Gotta go Fast" as the highest goal, and aware of the fact that the amount of computational resources and thinking time devoted to building fast starships will exceed by many orders of magnitude all human thought conducted so far, due to the importance of it...

I set myself to designing a starship to get to the Virgo supercluster (about 200 million light years away) in minimum time, as a lower-bound on how much of the universe could be colonized. I expect the future to beat whatever bar I set, whether humanity survives or not (it turned out to be about 0.9 c)

Now, most people focus on interstellar travel, but the intergalactic travel part is comparatively underexplored *(see comments).* We have one big advantage here, which is that we don't need to keep mammals around, and this lets us have a much smaller payload. Instead of delivering a vessel that can support earth-based life for hundreds of millions of years, we just have to deliver about 100 kg of Von Neumann probes and stored people, which build more of themselves. (The true number is probably a lot less than this, but as it turns out, it isn't harder to design for the 100 kg case than the 1 mg case because there's a minimum viable mass for dust shielding, and we'll be cheating the rocket equation.)

Before we get into intergalactic starship design (part 5), I want to take a minute to point out the field of Deep Time engineering, which is something that I just crystallized as a concept while working on this.

Note that whatever starship design you're building, it has to last for 200 million years, getting bombarded by relativistic protons and dust the whole way, and even with relativity speeding things up, you're still talking about building machinery that last for tens of millions of years and works with extremely high reliability the whole way. This is *incredibly* far beyond what engineering normally does, it takes god-like levels of redundancy and reliability, and if you've got something with moving parts, there's erosion by friction to consider, and also 200 million years worth of cosmic rays... I didn't focus on actual solutions that much, but just the awareness of the existence of tasks which require building machinery that works for hundreds of millions of years sparked something.

Engineers have shorter time horizons than you might expect. In environmental engineering (my major), we typically focused on a 20-50 year design life for building wastewater treatment systems. They're also dependent on the electrical grid for functioning. I *think* that I could design a 500-year treatment plant that also wasn't dependent on the electrical grid. It would take a while, bring in quite a few nonstandard considerations, and be far outside of the scope of normal design, and a bunch of standard approaches (like using energy-hungry air pumps to aerate the water) wouldn't work. A plant that does this would also have an enormously larger footprint than standard wastewater treatment plants.

Several-hundred or several-thousand year solutions are in a very different design space than standard solutions.

I should also make the note that we've figured out how Roman Concrete works, which is far more erosion-resistant than standard concrete (it lasts for several thousands of years, and is far more resistant to saltwater than standard cement), and this is why the Colosseum is still standing. Basically, you just use seawater instead of regular water when making it. Also the steel beams in regular concrete which give it tensile strength instead of mere compressive strength accelerate corrosion significantly. However, regular concrete takes a few hours to cure enough to apply weight, and cures fully in about a month. Roman Concrete takes *two years* to fully cure. And this is why very few places use Roman Concrete, even though it lasts over an order of magnitude longer. (I did find an article about a Hindu temple under construction that was using Roman Concrete, and was designed for a thousand years, though).

Even in civil engineering, the land of roads and bridges and buildings, you tend to see 100-year design lives at most, as well. I should note that there are tables that tell you the average magnitude of a 100-year flood (largest flood expected in 100 years), and these are used in design. And also the teachers mentioned that due to climate change, extreme weather events are more likely to occur than the tables indicate. But they didn't explicitly connect these two things, it was left unstated for the students to click together, and there was also an unstated implication that going to the higher-redundancy systems that'd handle 100 years+climate change would lead to people asking you why you're using 1,000-year flood numbers instead of 100-year flood numbers and the design wouldn't pass.

There are exceptions. The sea walls in the Netherlands are sized for 10,000-year flood numbers, and I got a pleasant chill up my back when I read that, because there's something really nice about seeing a civilization build for thousands of years in the future.

There's also the attempt to design nuclear waste storage that warns people away for tens of thousands of years, even if civilization falls in the meantime. This popular account is worth reading, as a glimpse into long-timescale engineering.

But in general, Deep Time Engineering is pretty underexplored, because it requires much higher costs, much higher reliability, a larger footprint, and about all of the machinery that you'd buy isn't rated for hundreds or thousands of years, there's no supporting infrastructure for engaging in construction projects of that design life.

The specific manifestations of it would vary widely by field and the specifics of what you're building, but in general it seems to be a discrete Thing that hasn't previously been named, and that our civilization neglects.

Building a 100-million year (or even billion-year) starship is an especially extreme example of this. For my specific starship design, the only thing that actually requires continuously running the whole time is the antimatter chilling system to get it to 0.1 K when the cosmic microwave background is 2.73 K (otherwise it heats up enough that you lose all your antimatter to evaporation against starcraft walls by the time you get there). This takes less than a watt of power to do, but keeping an antimatter cooling system (and storage system, although superconducting coils help immensely) continuously running for geologic timescales is a very impressive feat. Also, all the machinery for deceleration has to still work at the end of 100 million years of cosmic ray damage and such, and there's a part in there where end up firing a multi-gigawatt nuclear engine for a few millenia to target a specific star, which is also going to be extremely hard to design for that level of reliability. (imagine the radiation damage to the engine from that level of power, it won't be pretty).

Repairing nanobots help, but it's still going to be an impressive feat.

So You Want To Colonize The Universe Part 3: Dust

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Part 3a: Dust and Explosions

To a first approximation, there's exactly one thing that sets the speed limit on going fast in space.

Dust.

In the future, dust will be a Very Big Deal, as it's the dominant constraint on the most-important instrumental goal of going fast.

Anders Sandberg's paper pointed out dust as a constraint on interstellar probe design, but I didn't realize *exactly* how huge of an obstacle dust was until I started playing around with a spreadsheet.

To start with, interstellar (and intergalactic) dust has a size distribution, which tells you, for a given diameter range, how many dust grains there are of that diameter in a given volume.

At least for the range of 35-120 nanometers, (which shows up especially strongly in astronomical observations) it follows a power-law distribution, with an exponent of -3.5.

However, this dust isn't what we're worried about. There's erosion from protons and small dust hitting your dust shield at relativistic speeds, but doubling the dust diameter means it's 8x as massive and hits with 8x the energy.

At 0.9 c, 180 nm dust hits with 1 joule of energy. So all the normal dust isn't that much of an issue.

Going up to dust that's 1 micrometer wide, it hits with about 100 joules of energy, the energy of a firecracker. For all the following explosion comparisions, note that it's going to take the form of a super-narrow pinprick of kinetic energy directed on a single point, which is more destructive than a simple explosion, which radiates in all directions and has much of its energy dissipated as heat.

Destructive power keeps scaling rapidly, with about a factor-of-ten increase for every doubling in dust diameter, until we reach 20 micrometer dust, which hits with the energy of a grenade.

40 micrometer dust hits with the energy of 1.5 kg of dynamite. 86 micrometer dust hits with the energy of 30 bricks of C4. 0.18 mm dust hits with the energy of half a cruise missile. 0.4 mm dust hits with the energy of the Oklahoma city bombing. 0.86 mm dust hits with the energy of the largest non-nuclear weapon, the Russian FOAB. 8.6 mm dust hits with the energy of the Fat Man nuclear weapon, and 1.8 cm dust (a ball bearing) hits with the energy of a W87 fission warhead.

So, from about 1 to 20 micrometers, we get a pretty decent amount of boom that's shieldable. Whipple shields are the current standard for micrometeor impact. They have a protective thin layer that gets hit, turning the blast into a cone of shield-vapor, and then the force of the blast is dissipated over the area of a cross-section of the cone on the main bulk of the ship, which is much more manageable. However, I'm pretty sure that at relativistic speeds, the cone gets a lot more narrow, so they get less effective.

20 micrometers to about .1 mm is handleable if your ship is really damn sturdy.

.1 mm to 1 mm requires increasingly large dust shields that will start looking more asteroid-like, getting bigger than the mass of the rest of the ship, as they have to be that big to tank a hit from the largest non-nuclear weapon focused in a single tiny pinprick and narrow cone. Remember, by relativity, there's no difference between cruising through the interstellar medium at 0.9 c and being in the beam dump of a particle accelerator that's whipping stuff up to 0.9 c. Anything larger than 1 mm requires that most of the mass of the mission is composed of an asteroid, with the size of the asteroid rapidly scaling with dust size.

So, up to about 10 micrometers, we need a decent dust shield, 10 micrometers to 0.2 mm requires the sort of dust shield that can tank a hit from a cruise missile focused in a single point, and beyond that we basically have to whip an asteroid up to 0.9 c and attach a small ship to it with very rapidly scaling asteroid size. This requires quantities of energy that could blow the crust off a planet.

We know a lot about low-diameter dust that can be conventionally shielded with little issue, but we know very little about the distribution of higher-diameter dust, and that's the dominant constraint on mission speed and colonizing the universe. Of course, if we get a really bad distribution of higher-diameter dust, we can always go slower. For non-relativistic speeds, halving the velocity cuts the impact energy by a factor of 4, and for relativistic speeds, you get a lot more than that because of decreases in the relativistic-mass of the dust grain.

Maybe we'll get lucky and find that there's a sharp dust-grain cutoff beyond a certain size. Maybe we'll get unlucky.

Part 3b: Dust Distribution Facts and Implications

There are three relevant considerations I found, trying to work it out from first principles and astronomy facts. The first is that a dust size distribution implies a certain amount mass in a volume of space by doing the appropriate integral over diameter. The -3.5 exponent means that the amount of mass diverges. In order for the integral to converge and have finite dust mass in the universe, you need an exponent a hair below -4. But we don't know the diameter where the exponent shifts down to -4 or lower.

The second is that the asteroid belt has a size distribution of -3.5, and this is apparently characteristic of fragmentation processes. The reason there isn't infinite mass in the asteroid belt is because there's a size cutoff at the mass of Ceres. And we get the intuitive result that the mass of the asteroid belt is mostly in large asteroids.

The third consideration is that dust comes from many processes. Supernovae and dying stars floof out a bunch of dust into the environment. We found a supernova grain as large as 25 micrometers once, which is worrying. But most supernova dust is a lot smaller than that. For the millimeter-size dust grains, I imagine it'd come from planetary formation discs that got disrupted, which is a different process with a different dust production rate. So I'd expect different regions of space to have different dust size distributions, some of which might come with a natural mass cutoff. Maybe molecular clouds with forming stars are especially dangerous. Maybe the void between galaxies is mostly devoid of fatal dust (relative to the hydrogen density). Maybe dust gets more and more abundant as a galaxy ages so it's much more dangerous to travel in distant galaxies that have aged by the time we get there. We don't know, but it's probably modelable.

Now, there's two more things to note.

The first is that required-asteroid-mass to shield against the largest dust grain likely to be encountered is *ridiculously* sensitive to the scaling exponent, and pretty sensitive to how fast you're going. Pretty much, if you make your asteroid have twice the radius, you get 8x the mass, so you can tank 8x larger explosions, right? Well, maybe tankable explosion power doesn't scale linearly with mass, I'm unsure. But more importantly, your asteroid now sweeps out 4x the area because it has 4x the area, so you're 4x more likely to hit dust of a given size. Now, overall, you're still better off, but an increase in mass doesn't buy you nearly as much dust protection power as you'd naively assume, so dust still sets a pretty hard speed limit with quite rapidly scaling asteroid mass for traveling longer distances and higher velocities.

The second is that, due to the fact that dust is the dominant obstacle to going really fast, there will be an awful lot of optimization power directed at this problem, so the standard caveats apply about concluding that even a transhuman civilization can't do high-speed missions due to dust. Two obvious improvements I can see are making materials that are really good at dissipating massive pinpoint kinetic energy strikes, and finding some way to deflect dust. I think there's ways of charging the dust ahead of you and using a magnetic field to move it out of your way, but it's hard because we're mostly interested in large dust which is a lot less susceptible to these shenanigans, though I'd have to check. Also, any dust deflection system (and the power drain imposed by it) must be running full-time over the intergalactic voyage, which brings in the standard problems about making machinery that long-lasting.

Edit: In the three hours since typing this, I found that someone invented a completely novel deflection strategy I missed, and I also invented another one on the spot, proving my "don't underestimate the future" point very well. The one I didn't come up with is throwing a bunch of liquid metal droplets ahead of your ship, enough to ensure that a dust grain hits at least one of them and explodes, like an extremely long-distance whipple shield and very slightly accelerating the whole way so you can recapture the droplets and launch them back ahead of you. This has the issue of requiring continuous acceleration, and losing mass the whole way due to cosmic ray spallation of the droplets, and droplet vaporization when they get hit by smaller dust grains. Off the top of my head, it'd be pretty decent for an in-galaxy mission, but I worry that for intergalactic missions, the cumulative mass loss from droplets getting destroyed, and the propellant/continuous engine operation required to continuously accelerate the whole way, would be a bit much, plus it doesn't work on deceleration, just coasting. No, I'm not going to redo my design from scratch to take this into account, it's eaten enough time already. As for my insight, it's that if you have many spacecraft in a line, each can protect the next one, so the volume of space swept out by the fleet is much lower. Or, heck, you can just have the first dozen in the train being inert blocks of rock and only build important attachments for the stuff in the back.

So, for my mission, I assumed we're just directly tanking the impacts on a giant block of graphite, and there's a dust scaling exponent of -5 in intergalactic space (there are less protoplanetary discs which is where I think a lot of the scary dust comes from, and there aren't a lot there), a scaling exponent of -4 in interstellar space, and -3.5 closer to a star. As an example, shifting the dust scaling exponent of intergalactic space to -4.5 increases the mass of the asteroid we have to send by about 3.4 million times. This is what I meant by mass being ridiculously sensitive to scaling exponent size. The resulting dust shield mass per supercluster-ship (mostly dust shield though) is about 120,000 tons for a squat cylinder of graphite 42 m or about 140 feet long , or about 1/5th the mass of the titanic. Also we'll need about 30 of these for a 99.9% chance that at least one survives (higher survival probabilities are attainable by just sending more) It's far more efficient on a mass basis to send a fair few ships with a moderate chance of survival than to send one big ship with a 99.9% survival chance.

So in summary, dust size is the dominant constraint by far on how fast you can go, with unacceptably rapid-scaling mass increases as the exponent on the power law goes up.

Edit: Unless transhuman or mere-human ingenuity comes up with a way to cheat some part of the dust problem, in which case we're back in business.

So You Want to Colonize The Universe Part 4: Velocity Changes and Energy

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Part 4a: Speeding Up

Ok, so how do you get up to 0.9 c in the first place?

The common answer is "antimatter", but antimatter actually isn't that good for missions that are extremely relativistic. This is because of the Tsiolkovsky Rocket Equation, which applies anytime you're carrying your energy source and propellant onboard. Fortunately, it's very simple. $\Delta V = V_e * \ln(\frac{m_{full}}{m_{empty}})$. ΔV is your change in velocity. V_e is your exhaust velocity. And m_{full} is the mass of the rocket full of propellant, with m_{empty} being the mass of the rocket without propellant.

Eyeballing this, we see that the exhaust velocity gives you a decent approximation to how much you can change your velocity by, if you've got about 2 parts propellant to 1 part mass. Getting more velocity change requires an exponential rise in your mass ratio, and very rapidly gets to not be worth it, as pretty much no rocket has a mass ratio greater than about 20. Also, for stuff going really fast, the energy delivered is high, but the momentum isn't nearly as high, so high-specific-impulse rockets that whip their exhaust up to relativistic speeds emit an awful lot of energy, but have the sort of thrust typically associated with a fleet of asthmatic hummingbirds because they're very fuel-efficient and have a low mass-loss rate.

There are relativistic adjustments, of course, but the same basic behavior applies. Also antimatter annihilation has the problem of spending about 40% of its energy as gamma rays which just go in all directions and can't be used for thrust as a result, so you have to adjust the equation to account for that inefficiency.

So, even for a beam-core antimatter rocket, it's a bit more disappointing than you'd think. The classic example of this is the Frisbee Antimatter Starship, a hilariously ambitious starship design that is about *700 km* long, has about *160,000 tons* of antimatter aboard, blasts out *100 terawatts* of power, and achieves a measly 0.25 c. There have been notable improvements in beam-core engine design since then, but it's still too much for too little speed. And eyeballing it, the dust shield looks pretty puny, because it's sized for erosion from relativistic protons and small dust grains, not the cruise-missile-level dust grains I'm worried about.

Certainly insufficient for an intergalactic mission at high-relativistic velocities.

Edit: Found another beam-core antimatter starship design that does a lot better, the Valkyrie starship. Apparently the titanic size is partly an artifact of trying to squeeze high thrust out of an antimatter beam core so it doesn't take millenia to get up to full speed, and the antimatter beam core innately has very little thrust, so you have to crank up the power to enormous extremes. It's also partly an artifact of having a gamma-ray shield that's a lot bigger than strictly necessary with a different *configuration, which requires massive radiators, which means you have more dry mass to push, which means you have to make everything else bigger to compensate, which includes the rocket and the shield and you make the radiators bigger again... The Valkyrie claims the ability to get up to 0.92 c and back down with a 20:1 antimatter to ship ratio by mass, or 2,000 tons of antimatter, which is a bit much, especially because solid (anti)hydrogen isn't very dense, and if it's possible to go a given speed without getting destroyed by dust, the upcoming pair of approaches seems to be strictly better than any given antimatter rocket design because they completely dodge the rocket equation and the pesky ln term interfering with high-relativistic speeds, and also don't require enormous amounts of antimatter.*

But if you think about it, why does the energy source for getting the ship to go fast have to be onboard?

A far superior solution is a lightsail, a gigantic and very thin and very reflective sheet that you can fire a laser at to get your payload up to speed. Now, I didn't really design this part to a high degree of detail, and I think there might be issues with having a sufficiently large sheet not crumple like tissue paper under the stress of its launch. A spot for future work on making a realistic design if someone wants to take it up. You also need a gigantic floating laser lens to shoot the thing up to a distance of about 40 lightyears.

However, assuming you've got a dyson swarm available, you have more than enough energy on tap to bring whatever you'd want up to high-relativistic speeds. I was getting numbers that were something like an exawatt per ship (and again, we'd need 30 of them). So you'd need astronomical levels of energy-harvesting and lasers, and especially heat radiators, and this wouldn't be an immediate pulse, but you'd be cranking out multiple exawatts for decades at a time. Fortunately, assuming the ability to devote enough resources towards firin an astronomically large lazor, this is peanuts compared to the energy that's available from a star, and it lets you skip the rocket equation completely! No reason to be powered by antimatter when you've got the fury of a star-powered laser at your back, launching you unto the cosmic void.

Of course, transhuman technology might find something better, or a great refinement on the basic idea, but I'm still pretty confident that they'll skip designs subject to the rocket equation, that ln is a pretty punishing aspect.

But how do you slow down? That will take just as much energy as speeding up....

Part 4b: Slowing Down

Once upon a time, Robert Bussard had an idea for a starship. Interstellar space isn't empty, it has a very thin misting of protons in it. If you could do proton-proton fusion, you could have a giant magnetic scoop that funneled the interstellar medium into the rocket, where it'd fuse it for energy, then shoot it out the back, so it'd be gathering its own propellant and energy source as it went, and could get up to very relativistic speeds.

It captured the popular imagination, and then more calculations were done. It turned out to be bad. Really bad. So hilariously bad that it managed to achieve the elusive feat stated in [Reversed Stupidity is not Intelligence] about how a broken car couldn't go 200 mph in reverse, even if it was *really* broken.

The magnetic field produced a lot of drag. A hell of a lot of drag. In fact, the basic insight of "set up a large magnetic field in the interstellar medium" is the currently known *best way* to come to an absolutely screeching halt from relativistic speeds and is plausibly going to be an indispensable part of any serious interstellar mission. It produces so much drag that it is used to drop my starship design from 90% of lightspeed to 2% of lightspeed in 1.5 lightyears, pulling 1.5 g's of deceleration at the peak. This is a lot.

It turns out the way to decelerate from relativistic speeds doesn't take a rocket, it just takes a big loop of superconducting coil towed behind you and which slows down by dumping kinetic energy into violently shoving interstellar hydrogen away.

Now, there's a caveat. My design actually doesn't shed most of the kinetic energy. The analogy is that if you've got a crashing plane and a passenger on it, you're much better off attaching the parachute to the passenger than the crashing plane. Yes, you're going very fast, but you're only going through a lightyear and a half, so much less dust shielding is needed because you're much less likely to get hit in that space interval, so you can just separate from most of the dust-shielding block, let it streak through the galaxy at 0.9 c, (and get spectacularly wrecked in a violent kaboom by a piece of gravel at some point), and keep dumping shielding-mass as you slow, which makes it even easier to slow you down, and it feeds on itself until most of the remaining mass is actually in the superconducting coil.

There's some further details, one is about how to slow down from 2% of light speed (magsails don't slow you much at nonrelativistic velocities, but this is still far beyond the capabilities of almost all rockets that aren't antimatter, but there's another way to cheat this without propellant), and the other is about how you probably can't hit a specific star from 200 million lightyears away so you'll need some extremely beefy engine to get about 0.1% of lightspeed of ΔV on approach so you can boost sideways to aim at a specific star that looks promising, but those are implementation details that I'll go over later.

Part 5c: Power Sources and the Proper Use of Antimatter

Wait, didn't that previous stuff about needing an energy source for the final deceleration and the magnetic parachute, imply the use of power?

To a first approximation, there's exactly three energy sources that are compact enough for space missions (that we know about given present technology). There's antimatter, which releases about 100% of itself as energy. There's fusion, which releases about 1% of itself as energy. And fission of radioactive elements, which releases about 0.1% of itself as energy.

Obviously you'd want to use antimatter, right?

Well, it depends on how much you're using. You see, antimatter annihilation has extremely penetrating decay products. There's a bunch of very high-energy gamma rays (low hundreds of megaelectronvolts, MeV). There's a bunch of charged pions with a similar energy range, which go about 60 m or 60 ft (I forgot) before decaying into muons and neutrinos. Both muons and charged pions are really penetrating. We regularly find notable levels of muon radiation from cosmic rays 100 meters down in the earth, which is why many sensitive particle physics occur in deep mines, and pions are about equally penetrating due to a similar mass. Now, these pions and muons are much lower-energy than cosmic ray muons, so the situation isn't quite that bad, but they still have a tendency to require an awful lot of shielding. And a couple percent of the energy is radiated as kaons, which have similar issues, and can be charged or uncharged, the latter of which is unaffected by magnetic fields.

Amusingly enough, kaons contain a strange quark, which marks the only time the strange quark is actually relevant to a practical engineering design.

I'll get into more details later, but you'll require a pretty healthy weight of shielding mass unless you want to lose a bunch of your antimatter energy to space and hose every starship part in the vicinity with enough gamma radiation to give a person an instant-coma radiation dose in a few seconds. Yes, there are no people, just silicon chips, but radiation hardening isn't *that* advanced. (Yet)

So, in the limit of large amounts of energy, antimatter is definitely the best. But for smaller amounts, antimatter power's total mass is dominated by shielding mass, fusion's mass is dominated by the mass of whatever the most-compact fusion device of a given wattage the future can come up with (and neutron shielding, if they go for that type of fusion power), and fission... has a bunch of weight by itself, but you also need your nuclear reactor and the associated shielding.

My design has about 160 g of antimatter on board, which is both quite manageable to produce relative to the absurd 150,000 tons an antimatter starship needs *(Edit: see above, maybe not)*, and in the realm where it's kind of unclear which power source does best. I picked antimatter over "ultra-compact fusion reactor" mainly because it's sexy and more fun to speculate about. I used about 3 tons of shielding, so maybe fusion would be better if the future can make a fusion reactor that produces 10 megawatts and weighs under 3 tons. Or maybe a fission reactor could make it work, although the fuel alone (with a very efficient 20% burnup) would weigh a ton, and this neglects the rest of the reactor and neutron shielding.

Part 5d: You've Gotta Have Radiators

Vacuum is a great insulator! This is why vacuum-layer windows are awesome for insulation, because the only way heat can leave is by radiating away. This is a big problem in space travel, though. If you're cranking out a gigawatt of heat energy, your spacecraft will heat up until it's radiating a gigawatt in thermal radiation and glowing bright orange, toasting anything onboard that requires temperatures lower than molten iron to function.

So most of a practical spaceship's visual space is composed of radiators. Ordinary chemical rockets drop much of their energy in the form of hot escaping propellant, but fusion, fission, and antimatter rockets are very efficient with their propellant, so this avenue isn't available.

You'll need some way to deal with this if you want to do any space mission with a fission, fusion, or antimatter power source of any appreciable magnitude. Remember the Frisbee Antimatter Starship I mentioned earlier? 500 of the 700 km of length is just a gigantic radiator to dissipate the heat being absorbed by the gamma-radiation shield of the antimatter engine. I got my radiator for the antimatter reactor down to a paltry 1/4 of a kilometer, and I feel pretty proud about that.

An especially cool technology for this is the liquid drop radiator, which uses some sort of molten metal, and sprays it out as a sheet of fine droplets which has massive area, which is then collected and recirculated. It's unsuitable for really long missions because of very slow metal evaporation into space, but pretty nifty.

Due to the unsuitability of these for really long missions, the part in my design where there's a 10,000-year burn of a dusty-plasma-fission rocket, (The antimatter beam core is also acceptable, and probably has more manageable radiation shielding issues, but I wanted to highlight an obscure design that shows that fission can be surprisingly effective) for steering to a good-looking star, cranking out 3.5 gigawatts of heat the whole way, required something a bit more... solid. Diamond is the best heat conductor, and I'm assuming it's available by nanotech, so the giant cylindrical plug of graphite is also going to have extensible diamond radiator fins that will glow bright orange on approach.

Part 5e: More Notes On Antimatter Shielding

I think magnetic fields can confine the pions and muons and charged kaons to a finite region until they interact with something, dissipating their energy, and then you just need gamma ray shielding. Also, beams of charged particles can have energy extracted from them in a much more efficient way than dissipating heat. This would probably be used in a practical design, but I was being stubborn and wanted to capture the neutral kaons too, and figured "hey, if we're shielding gamma rays, is it practical to shield everything and drop the mass of the magnet and energy-extraction subsystem and have a vanilla turbine operating off the heat from the shield?" Basically, it'd just be a solid ball of shielding, and you shoot the antimatter into the center, where ~all of the radiation is absorbed, and the ball can be cooled down by a coat of liquid metal being pumped over it.

Now, the muons only show up later, and if you can stop the pions, the kinetic energy of the decay muons is low enough that they actually aren't that penetrating. So the task is to stop a flux of high energy gamma rays and pions and kaons. The dominant energy loss mechanism at these energies is inelastic collisions, where the pion or kaon smacks an atomic nucleus directly, blasting it to bits, which smack into other nuclei, and the energy level and penetratingness of the radiation drastically falls as energy drops, until the entire cascade is contained. For gamma rays, they smack an atomic nucleus directly, and turn into an electron-antielectron pair, which does a smaller cascade and is less penetrating. Still, even a more sensible design with charged particle energy extraction is going to need the gamma ray shielding (or just incredible radiation resistance) and weigh a decent amount.

Crunching the numbers, I discovered something hilarious. There's a number that is basically "what thickness of material gets half of your beam to interact", and for very dense elements, this gets thin enough to counteract the increased density of your ball. Lead is used in conventional gamma-shielding because it's cheap and pretty dense. But, as starship design is a very important priority for a civilization, they'd probably splurge on whatever material is optimal.

The optimal material turned out to be osmium (although iridium and platinum would be about as good). Yes, in starship design, where every gram counts, I found a perfectly legitimate engineering reason to stick a *3-ton ball of osmium* in the middle, as the antimatter reactor core. As a bonus, antimatter reactions tend to split heavy nuclei, so there's an energy boost from induced fission in the osmium, and osmium is really hard to melt so it can definitely accommodate the reaction.

So You Want to Colonize The Universe Part 5: The Actual Design

Alright, here's the actual design for an intergalactic mission to the Virgo Supercluster.

(1, 2, 3, 4)

Phase 1: Acceleration

To begin with, you use really big lightsails and exawatt dyson-swarm-powered laser arrays to get your fleet of 30 or so ships (really just a cylinder of some fancy graphite-based dust-impact-resistant material that weighs about 1/5 of the Titanic, and has about a 20 meter radius) up to cruising speed of 0.9 c for their 200-million-light-year voyage across the intergalactic void to the Virgo Supercluster, or at least where it's projected to be in the future by cosmic evolution simulations.

Phase 2: Coasting

By time dilation, this is dropped to 100 million years of waiting in an absolutely black void between the galaxies, where nothing of note happens except for occasional nanobot repairs, and keeping the antimatter at 0.1 K. And most of the fleet dies because they got hit by a grain of sand that's out in the galactic void for some improbable reason, but over those sorts of distances, even very improbable sand grains will show up at some point. However, several of them probably make it through, with the front looking pretty moth-eaten.

Phase 3: Target Selection and the Steering Burn

At a few tens or hundreds of thousands of lightyears out, the next phase can begin. Telescopic monitoring of the incoming galaxy, to build up a map of where the stars will be upon arrival, and the interstellar density distribution, and pick a good-looking one. Sticking a telescope out in front leads to the sensors getting destroyed by the proton flux, so they'll probably be shielded at the bottom of a tube of solid-but-transparent material.

Steering to the appropriate star location is done by a dusty-plasma-fission rocket firing sideways, which provides 200 newtons of thrust (equivalent to a model rocket engine), and emits 3.5 gigawatts of waste heat. For thrust that low with that much energy, the exhaust must be going really fast, and by the rocket equation, it gets the 0.1% of c change in velocity with only about 5% of the starship mass devoted to propellant, ie fissile uranium (or plutonium, bred from ordinary uranium by an onboard nuclear reactor, which is much more common and less prone to decaying over these time intervals and easier to store). So that's another 7,200 tons of uranium. An antimatter beam core rocket would have much less radiation damage, but it only has 1/10th the thrust for the same power output, which may end up being a bit much for the radiators if we crank up the power by 10x to compensate.

To dissipate the heat, the cylinder extends diamond fins, which start glowing bright orange at temperatures that'd melt iron.

Phase 4: Magnetic Parachute Deceleration

At about 1.6 lightyears to go, near a peripheral star with gas density about 100x lower than the sun (and about 5000x higher than intergalactic space), the bulk of the dust shield is cut free to fly through the galaxy, leaving two sub-ships with a dust shield of about 14,700 tons each, or about 10 meters radius, which move away from each other and unfurl a 1 km radius (or larger if you want to do this braking maneuver in a more flexible range of gas densities, or brake over a longer distance) loop of superconducting coil behind them, charged up from the earlier dusty plasma rocket firing, dragging behind the dust shield, and attached by carbon nanotube cables (or some other really high tensile strength material, their mass is low enough that I think carbon nanotubes might turn out to be overkill)

These reduced dust shields will disintegrate, cutting more and more fragments loose, over the 6-year braking time, as lower speeds require a smaller dust shield, which also reduces the intercepted volume of space, and a smaller dust shield can decelerate faster. Think of the star as the enemy gate (it's down), with a parachute above you, and cutting mass off the bottom of the payload to fall below you so you're lighter.

With the superconducting loop parachute, and the rapidly shrinking dust shield, a peak deceleration of 1.5 g's is reached, which the antimatter storage is going to have to resist to prevent a big boom. Enough mass is lost on the deceleration to 2% of lightspeed that the dominant mass is from the magsail parachute itself.

Phase 5: Electric Sail Deceleration

At some point around 2% of lightspeed, the superconducting loop itself is cut free, and the next phase begins, with three more ships cut free and separating. Each consists of a dust shield a measly 2.3 feet in radius, with the payload, antimatter storage, antimatter reaction chamber, power-generating machinery, 1/4 of a kilometer liquid-metal-droplet radiator, and the machinery for the next deceleration strategy all hiding in that narrow cylinder of safe space, about 170x longer than it is wide.

For the next 50 years, the antimatter reactor works through its stash of about 160 g of antimatter, cycling liquid metal past the osmium ball and running a very compact turbine off of the temperature differential induced by the liquid metal, and cooling off the metal in the 10 megawatt radiator which makes up most of the length, so the spaceship would look like an arrow glowing red. This is to power the electric sail.

The electric sail consists of about 10,000 50 km long fine fibers, which are charged up to 4 million volts so they all stick out away from each other. Think of the spacecraft as a dandelion seed with a really disproportionate parachute, 200x longer than the seed tail length. This electric sail repels protons, which causes deceleration, but they work way better at low velocities than magsails. Steering can finally be done by charging different fibers by different amounts. The long narrow radiator is in tension, not compression, since the electric sail is at the tail, so the ship can safely be that lone without collapsing. The charged fibers attract electrons, so we'll need a 1.5 megawatt electron gun at the tail. Total spacecraft weight at this stage is 18 tons, most of which is the radiator, antimatter reactor, and dust shield.

Over 50 years, this decelerates to 600 m/s near some suitable asteroid or comet.

Phase 6: Final Landing

Finally, the last 0.9 ton stage detaches to do a final landing.

600 m/s of change in velocity is easily attainable by conventional chemical rockets. We aren't taking off from orbit, we're dropping onto an asteroid, so the rocket of choice is the monomethyhydrazine-dinitrogen tetroxide thrusters that are used to alter the orientation of the space shuttle in orbit. Those rocket engines only weigh a couple kg, and the specific impulse is high enough that we only need 18% of the rocket mass composed of propellant, or 160 kg. The final stage lands on the asteroid or comet, and deploys the Von Neumann probes, the frozen state of the emulated people who decided to come along (they can't be active for the voyage because most of the ships are going to die by dust), and either some solar panels for probe energy, or a 490 kg mini-nuclear reactor for probe recharging if it's far from the sun (that ice isn't gonna melt itself...)

And done! No 700 kilometer antimatter starships needed.

Just a multi-exawatt dyson swarm laser array, some ridiculously big lightsails, giant blocks of graphite launched at 0.9 c, multi-million-year antimatter storage, a few thousand tons of fissile material to fire a nuclear rocket for thousands of years as steering, diamond radiators, superconducting magnetic parachutes, several tons of osmium, a few kilograms of antimatter, a quarter-km of liquid metal radiators, a 50-km radius "cosmic dandelion seed" of thin fibers charged to several million volts, good-old-fashioned chemical rockets, self-replicating probes, and repeated spacecraft sacrifices to the vengeful god of cosmic dust, may future civilizations punch him in the metaphorical face by making a design better than this, I know it's doable

Finally I can exorcise this special interest from my soul and get back to the fancier sort of math that ensures I live to see it happen.

(Also, Anders Sandberg, if you're reading this, hit me up, I've got an unrelated paper idea you might be interested in)