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Star Formation Rate in the Galaxy (R*, stars/year):

The star formation rate, much like the other terms of the Drake Equation, can only be determined by estimation. However, the estimation for R* is more informed and well-defined, because we can accurately estimate the number of stars in our galaxy today as well as the age of the galaxy, and their quotient gives a good approximation. The estimation of R* assumes two ideas: the formation of stars is constant over time in our galaxy, and the number of stars in our galaxy today is well-described by the range of 200-400 billion stars. The first is unlikely to be true, but there isn't evidence of extreme variation of star formation with respect to time in a predictable way, so R* as a function of time is likely to be close to a constant with small variations. The age of the galaxy is known to be about 13.7 billion years old, so this gives us a range (as stated in the textbook) of 14 - 30 stars per year formed.

To complete my estimation of R* I looked at a few other sources besides the textbook and found that in 2010 NASA and the European Space Agency found an estimate of the material created per year for star formation (given to be 0.68 - 1.45 solar masses), which divided by the average star mass gives a range of 1.5 - 3. Based on these two estimates, I conclude that R* is likely in the bottom of the textbook range, or top of NASA's implied range, so I take R* to be 14 stars / year.

Fraction of Stars Formed with Planets (Fp, planetary systems / star):

Fp ranges from 0.0 to 1.0 and describes the probability that a given formed star has a planetary system. The best method for determining Fp involves sampling visible stars and detecting exoplanets. Notably, stars are much brighter than exoplanets and thus much easier to detect. The Kepler telescope experiment probed stars in the sky to see evidence of exoplanets in the sky and found thousands of confirmed exoplanets. This has led astronomers to estimate stars on average having 1.6 planets, which puts Fp close to 1.0. Notably, for Fp to be 1.0, there would have to not exist a star without a planet, which is unlikely to be the case. However, all evidence from Kepler and other exoplanet detection missions point towards the idea that the vast majority of stars are a part of a planetary system, and therefore Fp approaches 1.

Because finding stars without planets is scarce and there isn't much evidence that large numbers of lone stars exist, I estimate that Fp is 0.99. This implies that almost every star has a planet, and therefore each one of the ~14 stars formed per year has a planet (for most years).

Average Number of Earthlike Planets per System (Np, Earthlike planets/system):

Ne represents how many Earth-like planets exist per planetary system, on average, and combined with fp and R*, estimate the number of Earth-like planets that come about each year. Ne can be broken down into the product of two terms, fs and np. Fs represents the fraction of life-liking stars, and np represents an average of the number of life-liking planets for each planetary system.

Based on our increasing findings of extremophiles and new planets having possibilities for life, I would estimate np to be greater than one, especially with our concrete example containing at least one life-supporting planet and potentially more (though that does not impact the average). I would put my estimate at about 2, to account for finding many Earth-like exoplanets in our galaxy, and I estimate the standards to support any life are quite low, given the extreme forms of life we find on our planet. For fs, I consider metallicity to be somewhat important to a planet's ability to support life, because of how important our diversity of elements has been for ecosystems, though there is likely a huge variety of metal ranges that can support life. I consider the variability of the star to be important so that the planet stays stable to support life. Stellar mass is mildly important; it seems to me that too massive of a star is not a big deal if intelligence develops quickly, but too small of a star can cause the planet to be tidally locked to the star based on its necessary proximity. If we ignore the planets with intermediate separations and include single, close, and wide binaries, we get an fs estimate of 0.95 * 0.99 * 0.25 * 0.7 = 0.164, which gives us a total of 0.328 life-supporting planets per planetary system.

Fraction of Earthlike Planets with Basic Life Forms (fl, life / life-supporting planet):

Fl, the probability of a life-supporting planet containing life, has everything to do with the formation of life. My estimate for the term is near to one because our planet stands as evidence (and our only evidence) of the quick development of life. The three components to creating life on a life-supporting planet are monomer formation, polymer formation, and the creation of life from polymers. The Miller-Urey experiment showed the ability to produce intermediate products of monomers with relative ease in a reducing environment. Though it speaks little to the ability to produce monomers in all conditions, the evidence humanity has is that monomer formation is likely to be possible in some environments, and polymerization seems likely as well due to the sheer number of monomers once a monomer-forming environment is created, giving many chances to make polymers. However, it is hard to determine the transition probability of polymers to simple life. Life needs reproducible instructions and many other self-sustaining properties. However, based on the rapid speed at which Earth developed life, I would play fl to be close to 1, about 0.9.

Fraction of Intelligent Life on planets with Life (fi, intelligent life / basic life):

Fi is one of the most difficult terms in the drake equation to estimate, because the transition from life to intelligent life has only been seen once, and intelligence is difficult to find and measure in species. Evolution clearly puts pressure for species to get better at producing children, but it isn't clear if evolution puts significant pressure on species to get smarter (smarter species haven't necessarily been more fit for survival). The only empirical evidence is the current existence of relatively smart species, and based on our model, it would be hard to develop multiple intelligent species because of how dominant the human species is. Because of the lack of evidence, and that there is a significant time frame for species to evolve, and intelligence appears to be dominant and persistent, based on humans on Earth, I put fi at 0.95, which shows a near certainty that intelligent life will come from basic life.

Fraction of Intelligent Life that Can Communicate (Fc, communication / intelligent life):

While there isn't much evidence to contribute towards the calculation of fc, fc is an easier term to theorize about, relatively. The set of species becoming intelligent and those that continue to develop towards communication is likely to be very high, because intelligence encourages itself, and technological innovation seemingly grows exponentially with time due to intra-species communication/globalization. The most important criterion to start technology development is extra-somatic storage of information, most commonly found in some sort of writing. Humans developed this in a natural way, through keeping ledgers of trade in early communities. I believe this mechanism is not rare; once a species can communicate within itself and becomes intelligent, ownership and trade are soon to follow. I would put Fc at 0.995, as I believe it is near certain that intelligent species will find a chain-reaction of technological advancement, which will lead to the ability to communicate. However, there isn't much evidence for fc besides humans' rapid transition to hunter-gatherer societies to space exploration.

Average Lifetime of a Civilization that Can Communicate (L, years):

L is another term of the Drake Equation that only has evidence drawing from humans' experience on Earth. Being the lifetime of a civilization, the most important things to consider for L are the avenues for an advanced civilization to end. The most obvious is some sort of disaster, such as a big impact from an object in space. However, large collisions are relatively uncommon, and the more prevalent avenue for a civilization to die out is the ability for a species to ruin its planet or kill itself off. In the case of humanity, the future looks grim. Humans appear to be ruining the planet at faster rates every year, and as a direct result of technological innovation, making it appear likely as a scenario for any civilization developing towards civilization. Moreover, technological advancements have also sparked artificial intelligence and nuclear weapons, both of which threaten small chances to end humanity if the environment isn't eroded too quickly. These avenues, and their apparent likelihood, put my estimate of L to be about 8,000 years, and it is only brought up because of the rare possibility of a self-aware species that controls itself and doesn't succumb to the greed that led to humanity's destruction of Earth, in which case the species would survive a long time.

Total Number of Civilizations Today: 8,000*0.995*0.95*0.9*0.328*0.99*14 = 30939

Comparison:

My first estimate (upon not knowing anything about the topic) was 0.3 civilizations in our galaxy, and my estimate at the end of the semester was 27211 civilizations. Between now and my first estimate, I've learned the course material and I understand some of the concrete facts surrounding the term (the age of the galaxy, what the components for life are, etc.) as well as how to frame my estimates by breaking down the terms coherently. Across the semester, my estimate increased a fair bit, and between the last discussion post and now, my terms have only adjusted slightly. The terms I changed either had to do with a poor understanding of the material (my estimate for R* went significantly down after doing more research) or from increased optimism. The representation of my change of estimations is that prior to the course, I wasn't particularly optimistic about the possibility of extraterrestrial life, and just thought of it as a joke, but now it seems that I strongly believe that there is life outside of our planet somewhere. The implications of this worldview are mostly that I'll take the possibility of aliens more seriously, and that I will try to broaden my views about other topics for which I feel closed-minded, because opening myself up changed my views in this course.

Limitations of Space Travel:

The main physical principle guiding the limitations of space travel is the speed of light. We cannot exceed the speed of light, and even approaching a fraction of it requires a great deal of energy and little mass. Rockets are the most natural way to approach space travel, with chemical, nuclear, electric, and antimatter being the primary routes of design. Chemical fuel has the limitation of a maximum s.i. of 500, and fuel is expensive in terms of added mass. Nuclear fission uses the power of nuclear bombs to propel a rocket forward. Unfortunately, the limitation of the fission approach is the potential danger of unleashing nuclear weapons for propulsion. Fusion is appealing because of its increased s.i., but its limitation comes because humanity doesn't currently have the technology to build a fusion rocket. Ion drives are actually promising as far as rockets go, and have a large s.i., but still fall under the limitations of mass onboard and don't have so much power to achieve everything humanity could want out of space travel. In terms of power, antimatter is extremely promising, but it holds the limitation of volatility; a rocket may be able to theoretically move quickly powered on antimatter, but the risks of leaking or explosion is huge.

Ultimately, rockets have limitations of themselves, and carrying fuel in any format is a recipe for disaster in limiting cases of space travel. A number of alternate approaches have been theorized, such as the Bussard Ramjet or light sails to travel, but technology remains a massive barrier for humanity in space exploration. Other limitations include the human cost of space travel; the technological cost is huge, and transporting humans even a few hundred light years requires multiple generations in a journey. Space travel is expensive and takes large amounts of time, and space is so big that it seems an impossible feat to traverse it all.

Analysis of *The Last Question*:

By Isaac Asimov, *The Last Question* provides a narrative example of analytical explanations with unbounded data. In a variety of plotlines, people ask humanity's supercomputer, Multivac initially, how to reverse entropy to avoid the heat death of the universe. However, at each occasion, the computer produces a relatively unhelpful response: "INSUFFICIENT DATA FOR MEANINGFUL ANSWER." The universe then begins its heat death, and finally the computer (now AC) figures out how to reverse entropy, and the story ends with the implication that the heat death is being reversed.

The story has many components that line up with our course content. For one, the reader experiences an aging humanity that has provided for itself well enough to be concerned about the eventual heat death of the universe, showing an intelligent civilization surviving for a great deal of time. The story centers around a piece of artificial intelligence that grows in knowledge. From our class, an AI which has the ability to answer deep meaningful questions is a dangerous object for a civilization, it is unclear to the reader why the computer hasn't developed sentience of any variety. Immortality is a topic covered in the story but not our class, but falls adjacent to our course material. Technology that extends the life of single organisms can push past the limitations of extra-somatic storage of information and can solve some of the complications of space travel. Finally, the story deals with the topic of exponential technological growth towards an asymptote. This is consistent with many ideas about space travel; it is easy to assume based on the rate of technological growth over humanity, easy space exploration is soon to come, but there is no certainty about technology's physical limits (in the case of the story, the heat death of the universe).

In conclusion, *The Last Question* covers many relevant topics from our class but doesn't fill in details about the advancement of technology or the development and restraint of these supercomputers. However, it illustrates a key point: computational power progresses to a bound, and some models are infinitely challenging to build (no computer can ever see all data in all combinations). In the story, the bound is set by the laws of thermodynamics and the size of the universe, but even simple applications of AI in the modern world see the limitations of finite computational power for machine learning.