The Drake Equation

The Drake equation, which we encountered in the very first lecture of this class, is a way to take the question "How many communicative civilizations are there currently in our galaxy?" and break it into several factors that we estimate as best we can. In this class we will go into detail about this equation. We will find that we now have a decent idea of the values of a couple of the factors, but that many are still guesswork. We'll do our best to make our guesses informed. We will also discover that some people have reformulated the equation by adding a number of other factors they consider crucial to having technologically adept life.

The remarkable and subtle effect of this is that, depending on how many factors you think appropriate, you can get the conclusions you want while appearing reasonable and conservative throughout. That is, if you think many civilizations exist, you can use the Drake equation to demonstrate this. If you think we are the only ones, you can get the equation to say that as well. With this in mind, we should approach the Drake equation as a way of framing our discussion as opposed to as a method of determining the answer rigorously.

The equation itself and its factors

The original form of the equation was written by Frank Drake in 1960 in preparation for a meeting in Green Bank, West Virginia. It says:

$$N = R^* \times f_p \times n_e \times f_l \times f_i \times f_c \times L \; . \tag{1}$$

Here:

- N is the number of currently active, communicative civilizations in our galaxy.
- R^* is the rate at which stars form in our galaxy.
- f_p is the fraction of stars with planets.
- n_e is the number of planets that can potentially host life, per star that has planets.
- f_l is the fraction of the above that actually do develop life of any kind.
- f_i is the fraction of the above that develop intelligent life.
- f_c is the fraction of the above that develop the capacity for interstellar communication.
- L is the length of time that such communicative civilizations are active.

Note that "fraction of the above" means that all the previous conditions have been satisfied. For example, when we consider f_c we assume that intelligent life has already developed.

The context of this equation was that Drake and others were considering how likely it would be that if we observed, say, radio waves from various stars that we might detect signals of intelligent origin. The general idea is that by breaking down the big question into various sub-questions, it is ultimately possible to make a reasonable estimate of the final answer. In doing it this way it is also implicitly assumed that no factor is so small as to render the others meaningless. For example, if you think that f_i is equal to 10^{-10}, then no amount of optimism about the other factors will compensate.

Are these the right factors, or do we have too many or too few? Obviously we can group some of the factors. For example, $f_p \times n_e$ is just the average number of potentially habitable planets per star in our galaxy. However, the point of the equation is to break up questions into manageable factors, so it is reasonable to avoid more grouping.

Estimates for N

We will now see that with all these factors it is possible to get a final answer that agrees with our preconceptions. If you want more discussion of each of the factors, see the sixth supplement.

We'll start with an optimist. We'll say $R^* = 10$ stars per year, a reasonable value. We will also say that $f_p = 0.2$, which is comparable to current fractions. Then we will assume $n_e = 2$, which is again reasonable given that in the Solar System there might have been at least four such places (Venus, Earth, Mars, and Europa). We will also take $f_l = 1$, basing this on the rapidity with which life appeared on Earth. For f_i we will say $f_i = 0.1$, and this is probably conservative. We will also allow $f_c = 0.1$, and will assume L =10,000 years; surely conservative given that advanced civilizations will have many ways to stave off disaster. Our total number is then $N = 400$. There should be plenty of active, communicative civilizations in our galaxy.

Now the pessimist. A better value is $R^* = 5$ stars per year. We also take the observed value $f_p \times n_e = 0.05$, and note that this doesn't take into account other considerations (e.g., this doesn't account for the requirement for low eccentricities). We will say $f_l = 0.5$, again probably high because of many things that could sterilize a planet. The fraction of intelligent life is low; say $f_i = 0.01$, because there are multiple happy accidents that were required in our case. The likelihood that intelligence would also be paired with manipulative capability is not great, so we also choose $f_c = 0.01$. For lifetime, we note that even if we avoid destroying ourselves by war, our resource usage will reduce us to a level that is not consistent with interstellar communication. We therefore pick L =1,000 years, and think that this is probably too long. Our total number is then $N = 0.0125$. With high likelihood, we are the only such civilization in our galaxy, and indeed in the entire Local Group of galaxies.

What is your best number?

How Common is Intelligence?

We will now explore some of the details that come in to the factor f_i in the Drake equation: if life has developed, how common is it that intelligent life will follow? As part of our answer we will need to determine what intelligence is. This is not an easy question, and there has been vigorous disagreement about it over the years, but after giving some possible answers we will discuss current animals on Earth other than humans that might qualify. We will then offer up some likely biological prerequisites for intelligence, talk about the development of intelligence in humans with its advantages and costs, and think about how competition and cooperation have played their roles.

What is intelligence?

This is a question that has occupied and divided researchers in psychology and neuroscience for well over a century. We will begin with some of the relatively uncontroversial aspects of intelligence, then address the unresolved issue of whether there is some monolithic and general "intelligence" or whether it must always be broken up into specializations.

Any creature with a claim to intelligence must certainly have some measure of:

- Adaptability to changes or a new environment. This was the weakness of computers always used by Captain Kirk on "Star Trek": when faced with an apparently all-powerful computer he would demand that it calculate the last digit of pi or give it a logical paradox and the hapless thing would go up in smoke.
- Capacity for knowledge, reason, and abstractions. Indeed, the capability for passing on knowledge (verbally, in writing, or in other ways) has meant that human society has evolved in a Lamarckian way. That is, if the previous generation has found out how to do something, yours can learn how to do it as well without waiting for genetic change. That's what has allowed us to progress to quickly. However, a capacity for abstractions and for finding patterns can also be a weakness. For example, many people are fooled by pseudosciences such as astrology because they remember when a horoscope appeared accurate and forget when it was inaccurate or just vague.
- Capacity for original thought. Here we have to be careful, because this can be a matter of degree rather than kind. Most people would agree that current-day computers do *not* have the ability to think original thoughts. They are programmed, and do what they are told without breaking the bonds of their programming. However, there are games such as chess in which computers are far better than the best humans, and can make the correct decisions in positions they have never encountered before. Is this original thought?

So far, so good. But can these be lumped into one general category of "intelligence"? One school of psychology, led by Charles Spearman and his heir Sir Cyril Burt in the early to mid 1900s, said yes. They gave intelligence tests to endless people and decided that although a given question on the test might rely on specific knowledge or particular experiences, the results of the test as a whole really did measure a single monolithic quantity. Another school, led by their contemporary L. L. Thurstone, suggested that intelligence is actually broken up into distinct categories. You could imagine a mathematical intelligence, a musical intelligence, a mechanical intelligence, and even something like an emotional intelligence that serves you well in social situations.

But why does it matter? From our standpoint in this course, it is of some interest because the tasks at which we in technological society need to excel are rather different from those required of our ancestors 100,000 years ago. Special aptitude in mathematics or music would have been irrelevant to individuals trying to find their next meal or avoid becoming something else's!

As always, the truth is undoubtedly between the extremes. It is clear that some people are better at abstract thought than at building things, or at language than at mathematics. Therefore, it is not as if intelligence is a single unbreakable quantity. On the other hand, our ability as a species to do so many different things indicates that our brains have not been hard-wired for a limited set of tasks. A question that we cannot answer is how typical this is of life elsewhere. We can, however, explore the abilities of other animals to see what they can offer. When we do so, we see a number of decently intelligent animals: chimps and bonobos (our nearest relatives), dolphins and their kin, even crows (which have been seen to make tools, not just use them). We should even think of collective intelligences, such as bees and termites (and their extension in the "Ender's Game" series). It happens that no other animal on Earth has our unique combination of high intelligence and manipulative capability, but maybe other places have produced multiple species.

Biological prerequisites for intelligence

I am confident in saying that intelligent life must be multicellular! Getting to that point, however, took a really long time on Earth. Life itself popped up rapidly; within 100–200 million years since the last major sterilizing impact during early bombardment. It could have been 10 million years, or 1 million; the very first life would have been so primitive it would be difficult to detect its traces now. However, multicellular life took a good three billion years from that point.

Why was that? Our single-example limitations make this tough to say, but one could imagine that successful cooperation between different cells, or incorporation as in endosymbiosis, was an extremely improbable activity that required profound luck. If so, it might be that we got lucky much more rapidly than average, and thus that intelligent life is very rare

in the universe. One could also imagine that there are metabolic costs associated with multicellular life that require a strong energy source, and that atmospheric oxygen was needed. If this is the case, the gradual rise of oxygen as a photosynthetic waste product might make multicellular life seem inevitable (although since photosynthesis already existed it is not clear to me why multicellular plants couldn't have emerged earlier).

From the cellular standpoint, the cell-within-a-cell aspect of organelles such as mitochondria and cell nuclei might have been the critical step. Another candidate is stem cells, which have been in the news over the last several years because embryonic stem cells have the potential to become any type of cell and are thus thought promising for future treatments of many diseases. The key to these cells is that they all start the same way, but in a fashion apparently controlled by chemical signals they can become more than 200 different types of cell. Therefore, rather than having to start off with hundreds of different cells, an organism can begin as one and differentiate with time.

There are other developments that appear helpful in our case, but it is not clear how widespread they must be. Sexual reproduction has a significant metabolic cost, but has the advantage that because the offspring are not clones of the parents, there is greater diversity and thus greater resistance to diseases. However, all animals are multicellular, yet almost none would qualify as having significant intelligence. Indeed, by far the most intelligent organisms on Earth are all mammals. It is not obvious why, for instance, reptiles could not be just as intelligent. It is also not obvious that intelligence is inevitable; there is a significant cost to big brains (they use 20% of our energy at just 2% of our mass, and birth is painful!).

The roles of competition and cooperation

Competition is critical to the development of species. Without it, there is no adaptation. It has also been essential in the development of human society. As an example of this we can take the classic question: why did the scientific revolution take place in Europe after the reformation, rather than in, say, China, which was in most ways more advanced at the beginning of that period? This is far from a settled question, but a thought-provoking answer I once heard is that at the time Europe was a collection of many small countries without a dominant nation such as the Roman Empire or a dominant religious entity such as the Catholic church, which had organized the area in centuries past. In contrast, China had for much of its history been ruled by at most a small number of large nations. The argument is that in a fragmented society such as post-Reformation Europe, any little advantage was important, and that this fostered competition and a willingness to think differently. Intriguing.

On the other hand, we are well aware of some of the negatives of competition. Battling ideologies, nations, and races have produced untold misery through the years, and as our destructive power grows it becomes increasingly possible that it could set us back a long

way. In smaller but important senses it also causes problems. For example, if everyone on Earth agreed to use less energy and work for alternative fuels, it could be argued that we would all benefit greatly. But in the near term, if everyone *else* sacrifices themselves, it is to our benefit to keep using easy fuels.

This brings us to the issue of cooperation. Why would you bother helping an old lady across the street? Why would a police officer risk her life to save someone she doesn't know? This is an interesting question, but we should realize that such behavior also occurs for non-humans. Different types of animals will sacrifice themselves to save the group; consider, for example, soldier bees that die in defense of the hive. Basically, what benefits the group benefits each individual.

Such cooperative behavior has played a major role in the development and use of human intelligence. It is also critical to our continued strides out to the stars. No matter how intelligent an individual is, she cannot get there alone. Cooperation is critical, and means that even an intelligent alien species will not get far if it is too solitary.

UFOs and Alien Visits

According to polls, about a third of Americans believe that we are being visited by flying saucers. If so, this would be profoundly important, since it would prove the existence of not just life, but technologically superior intelligent life. What is the evidence for this? In a larger sense, how much evidence should we demand to believe in alien visits? In this class we will go over the evidence and the psychology of belief. The net conclusion from my standpoint is that there is not a shred of definitive evidence for alien visits now or in the past, but that this demonstrates the eagerness people have to believe fun things :).

Levels of belief and the burden of proof

We will start by discussing several levels of belief, and how they apply to assessment of evidence. Levels include:

- True believer. The phenomenon in question has been established beyond any possible doubt, and no further data or disproof of apparent evidence will make a difference.
- Hopeful believer. Willing to accept disproof in individual cases, but still has a firm belief in the overall phenomenon. Consider Cubs fans, who are disappointed year after year but still believe starting the next season.
- Genuinely neutral. Has not made up mind yet, and thinks that arguments for or against a phenomenon are about equally strong. Alternatively, has simply not cared enough to make a judgment.

- Persuadable skeptic. Thinks that no current evidence for the phenomenon is enough for belief, but if strong enough evidence is presented they can accept it.
- Entrenched skeptic. Not only is current evidence inadequate, but no conceivable future evidence would be enough for belief.

All of us combine these approaches in different situations. For example, I am a true believer in gravity and that it makes things fall. If I were to see something that apparently contradicted this, e.g., my car slowly rising into the air, then rather than disbelieve in gravity I would assume that either some other force was countering gravity or that I was having a hallucination. Quite a fair number of UFO enthusiasts are in this category. What most people would consider weak evidence, they consider conclusive. If flaws or contradictions are pointed out, the reaction is anger or an assumption that somehow the all-powerful government has suppressed or altered the evidence. I'm happy to say, though, that by far the majority are hopeful believers. They think that various sightings and reports of abductions are too numerous to all be false, but are perfectly happy to hear counterarguments to any particular case.

You can, of course, have equally strong feelings on the other side. I am, for example, very close to an entrenched skeptic about telekinesis, which is movement of objects with just the power of one's mind. If I saw something that appeared to be such movement I would suspect a magic trick or that I was dreaming. It would take overwhelming evidence to convince me that it was real.

Phrased this way it may appear that there is symmetry between the levels of belief. In practice this means it may not be obvious how solid the proof has to be for alien visitation to be accepted. In particular, suppose that I report to you that I saw a flying saucer in the sky last night. Is it up to me to provide definite evidence, or is it up to you to prove me wrong?

The burden of proof issue underlies much of the discussion of UFOs and aliens. I've had plenty of people describe some incident to me and then challenge me to show that it had a natural explanation. However, I think we can phrase things a bit more objectively by asking how important or how unusual the claim is. If it is really spectacular, the bar is raised. As Carl Sagan said: "extraordinary claims require extraordinary proof."

For a practical example, imagine that I told you that yesterday I saw a friend of mine walking down the street. Your natural reaction would be to accept this statement without any further thought. But suppose I told you that yesterday I saw a 100 foot tall cyclops walking down the street. If you didn't just dismiss me immediately as insane, you would probably ask for absolutely ironclad evidence. But why? It comes down to the second claim being so overwhelmingly at odds with what you know about the world. If such things

existed it would have profound consequences for, among other things, the existence of other intelligent life forms. Therefore, you require stronger evidence than for everyday occurrences.

Similarly, if intelligent aliens are buzzing us every now and then, this would count as the most important discovery in the history of humanity. It would profoundly alter our conception of our place in the universe. As a result, I think it is clear that the evidence has to be unquestionable for us to accept it. With that in mind, how strong is the evidence?

Ancient monuments and ancient astronauts?

In 1968 Erich von Däniken published "Chariots of the Gods?", which sold millions of copies and convinced many people that evidence for alien influence is hidden in plain sight. The idea is that many ancient monuments such as the pyramids or Stonehenge could not have been created by the people of the time, hence aliens must have helped them. He made additional claims, such as that world religions originated after contact with aliens viewed as gods, but let's consider a few of the monuments and whether extraordinary explanations are necessary.

First, the pyramids of Egypt, specifically the Great Pyramid of Khufu (or Cheops). This is the only one of the seven wonders of the ancient world that is still standing, and it's impressive. On construction, this mighty monument was thought to be 147 meters tall and have a mass of some 5.9 million tons. Individual blocks had an average weight of about 2.5 tons. The four sides of the base are of equal length to an average of just 5.8 cm, compared with a length of about 231 meters, and are just a minute of arc away from a perfect square. The square's sides are beautifully aligned with the cardinal points of the compass, with one side pointing just 3 minutes of arc from true north (not magnetic north). To top it off, the ratio of the circumference at the base to the height at construction is within just 0.05% of the value of 2π, the ratio of the circumference of a circle to its radius.

Really impressive! von Däniken looked at this and concluded that it would have been far beyond Egyptians of 2560 B.C. to make such a huge yet precisely engineered pyramid. His conclusion was that advanced aliens had to be involved, and as we don't have historical records of the construction this is possible. However, following our principle that airtight evidence would be needed for such a hypothesis, we need to ask whether there is another possibility.

A variety of plausible suggestions have been made, and modern archaeologists have actually put some of them into action to show how this could be done. For example, using only technology that existed at the time, it was possible to carve blocks of that size from nearby quarries and transport them using wheels and inclined planes to the pyramid. With 100,000 men and 20 years, a structure the size of the pyramid could have been constructed. Another interesting suggestion is that the blocks could have been manufactured in place

with a kind of limestone concrete. Either idea would have been possible to use at the time, without aliens. It is also useful to note that the Great Wall of China, for which we have abundant historical records of its (human!) construction, contains about 120 times the volume of stone of the Great Pyramid, and was constructed and reconstructed over about two millennia. What it comes down to is that when you combine an all-powerful ruler with human ingenuity and a lot of manpower, remarkable (albeit non-functional) things can be done.

Another mystery that pegged von Däniken's alienmeter was the remarkable statues of heads on Easter Island. The largest of these weighs 82 tons, and many are far from their original stone sources. von Däniken again proclaimed the movement of these statues to be beyond the capabilities of the poor natives. It may not surprise you to know that anthropologists have since shown how, using only the tools available to the natives at the time, it was possible to cut the stone out of quarries, chisel them to resemble the statues, and move them long distances (using sleds). The statues have a long and complicated history, including the thought that the breakage of many of them was a last-ditch attempt to release bound magic and restore the ecosystem. Fascinating stuff, but nothing to do with aliens.

The rest of "Chariots of the Gods?", and indeed other evidence of this sort claimed by different authors, is all of this type. It basically comes down to argument by personal incredulity: "If I can't figure out how ancient people did this, it means they didn't, and the only alternative is aliens." In many ways it insults the capabilities of some pretty impressive civilizations. In any case, it certainly comes nowhere near the incontrovertible evidence we demand, so we need to move on to other claimed evidence.

UFOs

On its face, calling something a UFO is noncommittal: it means unidentified flying object, so theoretically a type of airplane that I can't identify is a UFO to me. Common usage, however, equates "UFO" with "flying saucer" or some other clearly alien conveyance. Large numbers of people are convinced that not only do flying saucers make frequent appearances in our skies, but that our government is actively covering up the evidence, sometimes with dire consequences for the heroic souls who blow the whistle. But how good is the evidence?

Some people date the first "report" to Ezekiel, chapter 1. In verse 4 we read "And I looked, and, behold, a whirlwind came out of the north, a great cloud, and a fire infolding itself, and a brightness was about it, and out of the midst thereof as the colour of amber, out of the midst of the fire." Later we learn about wheels within wheels and a number of other cool details.

There are, of course, multiple natural phenomena that can easily be mistaken for flying saucers, particularly given the difficulty that we have in recalling details correctly. Venus

has often been reported as a flying saucer (including by Jimmy Carter!). Meteorite fireballs are sometimes misidentified as well. Other phenomena include fascinating electrical effects such as ball lightning and "sprites". The main claims, however, try to focus on events that bypass such identifications.

In modern history, UFO sightings ramped up in 1947 after a private pilot named Kenneth Arnold reported nine brilliantly bright objects flying at incredible speed near Mount Rainier, Washington. Later that year was the famous Roswell incident, which to this day probably has the strongest grip on the imagination of any UFO report. The story is that on June 14, 1947, a ranch foreman named Mac Brazel noticed a strange cluster of debris some 30 miles north of Roswell. He said that he and his son saw a "large area of bright wreckage made up of rubber strips, tinfoil, a rather tough paper and sticks." UFO enthusiasts have latched onto this as proof of a crashed flying saucer, and this has made its way into endless realms of popular culture since its repopularization in 1978.

There has been such interest in this incident that in 1995 the Air Force released a report that said that the debris was in fact from a top-secret military program, but not one involving aliens. Instead, this was from Project Mogul, in which the Air Force flew high-altitude balloons with the intent of detecting sound waves from turbulence caused by Soviet atomic bomb tests. In response to claims after the fact of alien autopsies and the like at Roswell, the Air Force released a second report in 1997 which concluded that in addition to some specific hoaxes, some of the contributing factors included foggy memories after decades and even the occasional recovery of anthropomorphic dummies from other projects, such as Operation High Dive, which tested high-altitude parachutes.

How can we evaluate this? From our standpoint of requiring rigorous evidence for such an exciting discovery, Roswell obviously does not qualify, because the Air Force's explanation fits the facts and doesn't need the invocation of unknown entities. However, UFO enthusiasts stoutly deny that the Air Force is telling the truth. This is an example of a conspiracy theory. These play such a powerful role in UFO lore that we will take a minute to address these directly.

Conspiracy theories

This is a special category of hypotheses. Essentially, some powerful organization (often the government, sometimes a shadow group) is actively suppressing information. This might be about aliens, but has also been applied to events such as the assassination of President Kennedy. This organization also spreads disinformation so, for example, in the Roswell case it made up a story about a top secret program that appeared to explain the evidence but that is a diversion from the real story about aliens.

Conspiracy theories are special because they can never be disproven. Do you think you

have evidence that disproves my hypothesis? The government planted it. Why wouldn't anyone speak up about these world-changing finds? Because the government silences them. But then how can authors freely publish? Because they are heroes who have evaded the otherwise all-powerful organization. If the government is so good at covering up alien landings and preventing there from being any definitive evidence, why haven't they been able to put the lid on scandals such as Watergate? Because they want to *seem* incompetent to throw us off the trail.

What this comes down to is that if you think that you and a few other brave souls are the only ones who have penetrated the cloak of darkness surrounding the evidence, you are a true believer and nothing will convince you. However, let's return to the level of evidence we need. Does Roswell satisfy our criteria? Clearly not. It could in principle, if we had an actual alien ship, unknown metals, or alien bodies, but none of this exists.

Alien abductions

The last piece of evidence to examine is alien abductions, in which it is claimed that a person is actually taken aboard a flying saucer and then returned, sometimes after having invasive experiments performed on them. Some claims are undoubtedly deliberate hoaxes, but with thousands of reports it seems unlikely that all are lying. In fact, many of the putative abductees are rational, ordinary people. Hard evidence is entirely absent (e.g., alien flesh or alloys not found on Earth), but how could so many reports be anything but results of real abductions?

As we've emphasized throughout, the burden of proof is on those who claim these experiences, and with no hard evidence it fails our requirements. Nonetheless, there are some known phenomena that are very similar to these experiences as well as to reports from centuries ago. These are waking dreams combined with sleep paralysis.

Have you ever had a time, just before going to sleep or just after waking up, when you are not quite awake but can see your bedroom and things in it? In such a situation you can have a waking dream, in which other things and entities appear present. For example, I have had times when I have awakened in the middle of the night realizing that someone is looking at me through my bedroom window. After hiding and then waking up a bit more, I realize that (1) my bedroom is on the 15th floor of my building, and (2) my shades are drawn, so real as the experience seemed it didn't happen! Compounding the sensation of fear that these dreams can produce is that we have a natural state called sleep paralysis. When we sleep we don't move as normal, which is good as it prevents us from walking off a cliff at night. However, when awakening, it can happen that for a few seconds one can't move, which can be particularly terrifying if one is also having a waking dream that there is some other thing in the room. Combined, these effects explain centuries-old reports of attacks by demons at night, and many of the reported instances of alien abduction. Once

again, the lack of hard evidence means that we cannot conclude that aliens are among us.

Some perspectives

In my opinion, most people who report strange things in the sky or terrifying experiences at night are doing their best to do so accurately, without fabrication. However, nothing passes the strict standards that we must set for such important claims. In addition, one has to wonder about the plausibility of advanced aliens acting as they must if the reports are real. For example, how could they avoid definitive detection (and I'll remind you that there are endless public telescopes and sensors that could not all be censored at once) but be seen constantly by ordinary people? To put it another way: http://xkcd.com/1235/. If their intent is to sneak around, why would they do this? That is to an extent an unresolvable question about alien psychology, but note that the distance they would have had to travel is so enormous that it boggles the mind that they would expend such resources for no obvious purpose. Also note that much of the probing that they are reported to do during abductions speaks to staggeringly primitive biology given the required mastery of the physical sciences needed to get here at all.

Fundamentally, I think that reports of aliens are fascinating reflections on human psychology. It would be cool if they were real (although maybe not; watch the Twilight Zone episode "To Serve Man" for some chills), but the odds are strongly against it.