Life in the Universe

"Are we alone?" is a question that is both profound and eternal. People have probably been asking it in one form or another since the dawn of history. Early on, of course, no one knew whether other parts of the Earth contained humans or monsters, which is probably a major driver behind many cool myths. Now we have explored enough of the Earth to know that dragons aren't waiting around the next bend, but we have seen life in places that we could not previously have imagined: near undersea volcanic vents, in frozen or acidic wastes, and even miles deep in solid rock.

Our search for other life has therefore moved outward. Could life exist elsewhere in our Solar System? How about orbiting another star? Would we feel excited by alien microbial life, or do we hope for E.T. or Mr. Spock? If intelligent aliens are out there, is there a chance that we could communicate with them?

We are at a disadvantage in searching for extraterrestrial life of any kind, simply because we only know of life on our planet. In particular, we therefore don't know how many of the circumstances that have allowed such diversity of life on Earth are essential for life elsewhere. Must the host star be similar to ours? Does life have to develop on a planet, or could it be the moon of a planet or elsewhere? If a planet, need it be in an orbit similar to ours? Does it have to have the same composition, and be the same size as ours? Our natural tendency is to look for situations similar to ours, but that may be too restrictive.

In this class our task will be to explore various aspects of life in the universe. This will include relevant aspects of cosmology, star and planet formation, chemistry, biology, and of course specifically life on Earth. We will also have some fun speculating about how we would detect life elsewhere (intelligent or otherwise) and current attempts to do so.

I do want to issue one warning. Evolution has been central to the development of life on Earth, and is such a simple and general process that it undoubtedly plays an equally essential role in life anywhere. As a result, we will have several classes on evolution, both the fact that it has happened (which is established as clearly as any fact in science), and the theoretical underpinnings (which, like any theoretical concepts, are under development at the frontiers). If for any reason you are offended by evolution, this really isn't the course for you and I want you to know that now.

What is life?

As our first step towards a search for life, we might want to define what life is. Surely that can't be too difficult? Let's take a quick poll. How many people think that a rock is alive? A snowflake? Clay? A virus? A bacterium? A fly? A person? I'm guessing that most of you would say that the first three are not alive, that the last three are, and that you are less certain about the virus. However, as we'll discuss when we go over possible origins of life, there are reasons to think that some clays have properties similar to primitive life, and snowflakes also fit some of the definitions (although I'd have a tough time assigning life to a snowflake). What definitions have people used for life?

There is no general agreement, but most people feel that the following conditions are necessary for life (see the Wikipedia page on life):

1. Homeostasis. Living things need to have a regulated internal environment. This need not be perfect regulation (note that you can survive a fever, and cold-blooded animals can change their body temperature significantly), but reasonable limits need to be maintained.
2. Metabolism. There must be intake of matter which is then processed to extract energy and build up new components of the living thing.
3. Growth or reproduction. During at least some phase of the existence of the living thing, it must be able to grow or reproduce.
4. Adaptation. It is necessary that, possibly over many generations, the living thing must be able to change in response to its environment.

For the large complex life that we're used to, these are obvious. However, very small life can make even these basic requirements less obvious. For example, there are spores and bacteria that can go into a state in which they don't eat or grow; they just sit there. This can happen if they are in an environment without any water. Even with larger things, it can be that some members of the species are always, inevitably, sterile (such as with ant workers). There are also much larger examples of sterile things, such as mules or ligers, although they do grow (which is why we said grow *or* reproduce above).

You'll note that we carefully avoided saying that it is essential for life to be made of cells, because viruses don't have cells. We also note that viruses and some bacteria actually can't perform certain critical biochemical operations by themselves, needing a host organism. Do we then consider these to be independent life? We also have to realize that the very earliest homeostatic, metabolizing, growing/reproducing, adapting organisms on Earth had to be much simpler than what we see now (even simpler than viruses). It seems highly likely that the transition between life and non-life was gradual.

From the fundamental biochemical standpoint, even among things that most people would say are definitely alive there are wide variations. All the big things we're used to use oxygen in one way or another as their basic source of energy. However, there are microbes that instead use sulfur or nitrogen as their basic source. One consequence of this has to do with how we would establish that a planet around another star has life. It has been suggested that since free oxygen doesn't last very long in most atmospheres, if we see the spectral signature of oxygen then there must be life. That may or may not be true, but the existence of bacteria and archea that are otherwise powered means that the absence of atmospheric oxygen does not have to rule out life (indeed, in the first billion plus years of life on Earth, atmospheric oxygen was rather low).

The Drake equation

As you can see, we are in a position of great uncertainty about extraterrestrial life. Estimates of the probability that there currently exist other intelligent civilizations may seem completely doomed. It is, however, useful as an organizational tool to follow the path first laid out by Frank Drake in 1960 at Green Bank, WV as preparation for a historic meeting on searches for extraterrestrial life.

What Drake pointed out is that although we may not know the final answer to how many current civilizations to expect, we can write the answer as a product of factors so that we see more clearly which factors are uncertain, and which are basically under control. We'll see this equation later in the class after we've gone over a number of the inputs, but it's fun to give it a shot now. One warning: after Drake's original introduction of his equation, many variants have been proposed. If you increase the number of factors, you can get the answer to be as small as you like. We'll start with a slight modification of the original:

$$N_c = N_* \times f_p \times n_e \times f_l \times f_i \times f_c \times f_s \ . \tag{1}$$

Here N_c is the number of civilizations with which we could potentially communicate; $N_* \approx 4 \times 10^{11}$ is the number of stars in our galaxy; f_p is the fraction of those stars that have planets; n_e is the number of potentially inhabitable planets per star that has planets; f_l is the fraction of those planets that develop life; f_i is the fraction of the ones that develop life that eventually develop intelligent life; f_c is the fraction of the ones with intelligent life that release detectable signals of their existence; and f_s is the fraction of the Galaxy's lifetime that they do so.

The only very well-known factor here is N_*. Discoveries of extrasolar planets over the last 10–15 years have given us a decent handle on f_p, although as we'll see the detections are strongly biased towards planets that have a small probability of hosting life as we know it (i.e., Jupiter-mass planets closer to their star than Mercury is to the Sun). Still, let's take some guesses at the values of the rest of the factors. What product do we get? Most groups are optimistic enough that the number turns out to be reasonably large. The basic cause of this, of course, is that N_* is so tremendously large.

However, suppose that we are convinced for other reasons that we are alone in the galaxy. It is easy to put in other factors that reduce the value practically as much as we would like. For example, it has been argued that the following things could be crucial:

- The host star needs to be like the Sun. The argument goes that much more massive stars don't live long enough for life to develop, and much less massive stars have tremendous flares that would wipe out life. This introduces another factor f_{Sun}, which is about 0.1.
- An orbit like Earth's, and a planet very like Earth in that orbit. It has been suggested that a high-eccentricity orbit (rather than the nearly circular one we have) would subject any life to variations too extreme to survive. Also, if the planet in question is too small it can't retain an atmosphere and will lose its internal heat quickly. A planet that is too large might have any solid surface buried under an atmosphere too thick for light to be used as energy. This might put in another couple of factors: f_{orbit} and f_{Earth}, each of which are comfortably less than 0.1 in some people's reckoning.
- Other special characteristics about the Solar System and Earth in particular. For example, it has been proposed that Jupiter acts as a critical shield for us against marauding asteroids, and that having a large moon stabilizes the Earth's rotation axis in a way that allows life to develop. Again, we could put in factors f_{Jupiter} and f_{Moon} and argue that each is conservatively no more than 0.1.

That gives you a taste; it has also been suggested by those who want us to be alone that our position in the Milky Way galaxy is specially privileged, for example. If we think that there are millions of civilizations around, we have to answer a question first posed by Enrico Fermi: where are they, then?

Barring truly amazing timing, we don't expect to be able to resolve in this class whether life elsewhere (even microbial life) exists. However, the goal is to understand the context and current searches, and to thus get a little closer to comprehending the vastness and diversity of the universe.