The Drake Equation

- \( n_s \), total number of stars in Galaxy of the “right” type (6 billion)
- \( f_p \), fraction of these stars with planets (5%)
- \( n_e \), average number of planets orbiting those stars that have right size and are in habitable zone (100%)
- \( f_\ell \), fraction on which life actually develops (100%)
- \( f_i \), fraction on which evolution produces intelligent species \( (10^{-10} - 1) \)
- \( f_c \), fraction of intelligent species that develop ability and interest to communicate (100%)
- \( L \), average lifetime of civilizations
- \( T \), age of Galaxy \( (10^{10} \) years)

\( L/T \) gives the fraction of civilizations that currently exist.

\[
N = n_s f_p n_e f_\ell f_i f_c L / T
\]

\[
N = 6 \times 10^9 \cdot 0.05 \cdot 1 \cdot 1 \cdot f_i \cdot 1 \cdot \frac{L}{10^{10} \text{ yr}}
\]

\[
N = 0.03 f_i L
\]
**Primary Uncertainties in the Drake Equation**

$f_i$ – The development of intelligence

- Limited availability of raw materials, forces evolution of complex processes to develop alternate, more reliable, sources
  
  Example: original organisms relied on limited supplies of $\text{H}_2\text{S}$ and anaerobic photosynthesis.
  
  Aerobic photosynthesis and metabolism used more common materials.
  
  By-product: $\text{O}_2$-rich atmosphere and ozone layer

- Specialization in cells: development of eukaryotes and organelles by symbiosis

- Sexual reproduction: permits greater genetic variation in offspring

- Development of multicellular organisms, probably by symbiosis, triggered Cambrian explosion of phyla, as recorded in the Burgess Shale

- Development of nervous system/brain: elimination of DNA-length bottleneck

- Convergent evolution argues in favor of intelligence as a survival optimizer.
• The generally increasing maximum encephalization quotient of other mammals, like dolphins and whales, also supports large values for $f_i$.

• Note, however, that all mammalian species do not show such increases. But if on other planets, there are several competing species, this fact is unimportant.

Lacking other information, $f_i \approx 1$. 
$f_c$ – The development of civilization and technology

- Competing hominid species (H. erectus, Neandertals, H. sapiens) coexisted (only H.S. was an omnivore) 200,000 yrs ago
- Development of technology and communication requires certain physical attributes (hands, living on land, ...?)
- Development of communication has been cultural, not biological
- Development of written language, beginning with art, 30,000 yrs ago
- Development of agriculture 5000 yrs ago
- Development of alphabet (Sumerians) 3500 yrs ago
- Development of printing press 550 yrs ago
- Development of radio 100 yrs ago
- Development of electronic information storage 50 yrs ago
- Progressive transformation from individual to collective intelligence

Note:
- Independent evolution of key technologies: agriculture, alphabets, numbers, metallurgy, astronomy
- However, note that wheel was invented only once (Sumeria), and the zero relatively rarely

Lacking other information $f_c = 1$.

Simplified Optimistic Drake Equation: $N \approx L$
Civilization Lifetimes

- Overpopulation, leading to resource depletion or irreversible pollution

\[ \frac{dN}{dt} = N(b - d) \]

\( b = \frac{1}{30} – \frac{1}{60} \) (4–2 children per woman)
\( d = \frac{1}{60} \) (1/life expectancy)

\[ N = N_0 e^{(b-d)t} \]

Population grows by the factor \( e \approx 2.7 \) every \( \frac{1}{(b - d)} \) years \( \geq 60 \) years

Malthus in 1798 first proposed that resources tend to grow linearly, but population grows exponentially. If left unrestricted, populations grow until they exceed carrying capacity of environment. He showed this had happened before in human history with catastrophic consequences (e.g., Mayan, Mesopotamian, Norse, Angkor and Easter Island civilizations) and predicted it would again.

However: industrialization, readily available social services (i.e., birth control) and improved living conditions generally lead to a decrease in the birth rate. From 1950 to 2005, the number born per woman decreased from 5.01 to 2.65 worldwide, and by 2050 is expected to decrease to 2. This could lead to a peak in population around 8 billion by 2050. Furthermore, new resources are found at faster rates due to technological and scientific advances. But underinvestment and pollution, including irrigation salt poisoning, could still be insurmountable problems.
Limits To Civilization Lifetimes

- Warfare
  - Nuclear
  - Biological

But these factors are inherently driven by overpopulation.

- Natural catastrophes
  - Asteroid or comet impact
  - Solar evolution – increasing solar luminosity, eventual red giant phase
  - Gamma ray bursts, massive supernova or merging neutron stars and/or black holes in binaries (within 5–10 kpc)
  - Supernova (within 0.1 kpc)
**Galactic Habitable Zone**

- Metallicity - too much: hot Jupiters destroy Earths, or Earths become too big; too little: no Earths or too small Earths
- Supernovae or gamma ray bursters - cannot be too close too frequently
- Biological evolution time - $4 \pm 1$ Gyr
## Future of Civilizations

### Kardashev Civilization Types

<table>
<thead>
<tr>
<th>Type</th>
<th>who</th>
<th>Energy used compared to us</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>bee colony</td>
<td>1/1 trillion</td>
</tr>
<tr>
<td>I</td>
<td>us</td>
<td>1</td>
</tr>
<tr>
<td>II</td>
<td>uses all Sun’s energy</td>
<td>1 trillion</td>
</tr>
<tr>
<td>III</td>
<td>uses all Galaxy’s energy</td>
<td>1 trillion trillion</td>
</tr>
</tbody>
</table>
Dyson Sphere

A result of a Type II civilization. Since 100% of the star's energy is intercepted by the sphere, which would re-radiate it in the infrared, the energy output of the star would be altered completely. Dyson proposed a shell-like structure, but this has numerous flaws:

- A shell would have no net gravitational interactions with its star and would drift without some form of propulsion. Collision with the star would be catastrophic.
- Anything on the inside of the Dyson sphere would not be gravitationally attracted to it and would fall into the star if not attached.
- Strength of shell material would have to be enormous, well outside the parameters of any known material.
- If all planetary material were used, a 1 AU Dyson sphere could be 3 m thick, but only 10 cm thick if H and He were excluded. If only the inner planets are used, the thickness becomes less than 1 cm.
- The equilibrium temperature at 1 AU is 360-380 K (too hot for humans).

A better design: individual self-propelled habitats, but gravitational interactions would result in loss of orbital stability and occasional eclipses. The best design would be floating individual habitats using the balance between radiation pressure and gravitation. Requires a large “light sail” area for each habitat.
**Ultimate Limit to Lifetime**

- Technology can be developed to protect against all astronomical catastrophes, like supernovae, gamma ray bursts, meteorite/comet impacts, solar changes.
  - For example, civilizations can move to other planets to escape solar luminosity increase.
  - Or they can move to other solar systems to escape red giant phase.
- Thus, the ultimate lifetime depends on the ultimate fate of universe.
  - An open or critical universe expands forever, but slowly cools off, and its usable energy disappears.
    Dyson hibernation strategy can preserve life subjectively forever.
  - A closed universe eventually recollapses, so there is an apparently finite lifetime.

However, subjectively, an infinite lifetime is theoretically possible if uploading (the process of transferring mental structure and consciousness to external carrier) is possible.

Subjective time different than clock time because computers process information millions of times more quickly than brain cells.

Tipler argues that life alters the ultimate fate of the universe to force an “Omega Point”, which has an infinite subjective lifetime.
**Distance to Nearest Civilization**

- Sun is about 8000 pc from nucleus of Galaxy
- The average density of stars in the Galaxy is $\rho = \text{Number/Volume} \approx 1.4 \text{ pc}^{-3}$.
- Let $N$ be the number of civilizations, and $N_*$ the average number of stars we would have to search to find a civilization $N_* = 4 \cdot 10^{11} / N$.
- If $R < 200$ pc, the Galaxy looks like a sphere: $N_* = 4\pi \rho R^3 / 3 = 4 \cdot 10^{11} / N$.
- $R^3 = 3 \cdot 4 \cdot 10^{11} / (4\pi N \cdot 1.4)$, or $R \approx 4085 / N^{1/3}$ pc.
- Instead, if $R > 200$ pc or $N < 8500$, the Galaxy looks like a disk.
- $N_* = \pi \rho R^2 \cdot 400 = 4 \cdot 10^{11} / N$; $R^2 = 4 \cdot 10^{11} / (1.4\pi N \cdot 400)$ or $R \approx 15,000 / \sqrt{N}$ pc.
# Difficulty of Communication

<table>
<thead>
<tr>
<th>$N_\ast$</th>
<th>$R$ (pc)</th>
<th>$N$</th>
<th>$\tau$ (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2</td>
<td>1</td>
<td>$8 \cdot 10^{11}$</td>
<td>6.5</td>
</tr>
<tr>
<td>500</td>
<td>10</td>
<td>$8 \cdot 10^{8}$</td>
<td>65</td>
</tr>
<tr>
<td>$5 \cdot 10^5$</td>
<td>100</td>
<td>$8 \cdot 10^{5}$</td>
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<td>2117</td>
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<td>65,000</td>
</tr>
<tr>
<td>$4 \cdot 10^{11}$</td>
<td>25,000</td>
<td>1</td>
<td>163,000</td>
</tr>
</tbody>
</table>

$\Leftarrow N = L = \tau$

$\Leftarrow N = 0.01L = 0.01\tau$