Order-of-Magnitude Estimation
Habitable Planets (Level 2)

The Question

How many Earth-like planets are there in the Milky Way Galaxy?

Background

We often define potentially habitable planets as "Earth-like", since as far as we know life can only develop on planets with conditions similar to our own. This generally means that the planet orbits a star similar to the Sun, which is a slightly-less-than-average star in terms of mass, that the planet has a mass similar to Earth's, and that it is orbiting in the "habitable zone". This is defined as the region where liquid water can exist, and for a planet of similar mass to Earth is at a radius similar to that of Earth (defined as one astronomical unit, or 1 AU). We can use these pieces of information to estimate how many potentially habitable planets are in our Galaxy!

Guiding Questions

Here are some things you may need to consider:

- How many stars are in the galaxy?
- How many of these have masses like the Sun?
- How many of these have planets?
- How many of these planets are Earth-mass?
- How many of these orbit within the habitable zone?

The Solution

In the guiding questions you might notice the phrase "of these" comes up a lot. This implies that starting with the number of stars, we just need to multiply by a series of fractions to get to our final number:

$$N_{\text{habitable}} = N_{\text{stars}} \times f_{\text{mass}} \times f_{\text{planet}} \times f_{\text{planet mass}} \times f_{\text{orbit}} \tag{1}$$

There are about 100 billion stars in the galaxy (you could estimate this by knowing the rough shape of the galaxy, its size, and the typical separation between stars).

Since the Sun is a less than typical star, we'll say that about 20% of stars are Sun-like in terms of mass. Astronomers are finding that the vast majority of stars have planetary systems (e.g. the many discovered in recent years by the Kepler mission), so we can safely assume that $f_{\text{planet}} = 1$. Detecting Earth-mass planets is difficult, so the fraction of them is difficult to estimate — since we're not sure, we can just guess it is around half.

Liquid water can only exist on Earth within a certain range of orbital distances. Too close to the Sun and it will evaporate, but too far and it will freeze. The amount of solar energy that Earth receives is inversely proportional to the square of its distance. That means that if you *increased* its orbital radius by a factor of two, it would receive 1/4 ($1/(2^2)$) of the energy. If we estimate that if the energy increased or decreased by 5% to boil or freeze, or a range of 10% total, then this equates to a possible range in distance of $1 - 1.1^2$ or about 25%. If we assume planetary orbits are uniformly distributed (i.e. any orbit is as likely as another), then 25% will fall within the habitable zone of their star.

This means that:

$$N_{\text{habitable}} = 10^{11} \times 0.2 \times 1 \times 0.5 \times 0.25 = 3 \times 10^8 \tag{2}$$

There are about 300 million potentially habitable planets in our Galaxy!

Education Standards

This OoM Estimation problems meets the following standards in **bold**:
***Next Generation Science Standards (NGSS)**:*

- Physical Sciences
  - **Matter & Its Interactions**
  - Motion and Stability: Forces and Interactions
  - **Energy**
  - Waves and Their Applications in Technologies for Information Transfer
- Life Sciences
  - From Molecules to Organisms: Structures and Processes
  - **Ecosystems: Interactions, Energy, and Dynamics**
  - Heredity: Inheritance and Variation of Traits
  - **Biological Evolution: Unity and Diversity**
- Earth and Space Sciences
  - **Earth's Place in the Universe**
  - **Earth's Systems**
  - Earth and Human Activity
- Engineering, Technology, and Applications of Science
  - Engineering Design

***Common Core Standards (CSS)**:*

- **Counting & Cardinality**
- **Operations & Algebraic Thinking**
- **Numbers & Operations in Base Ten**
- **Number & Operations — Fractions**
- **Measurement & Data**
- Geometry
- **Ratios & Proportional Relationships**
- The Number System
- **Expressions & Equations**
- Functions
- **Statistics & Probability**