HACK-4-SAGES PROJECT IDEA EXAMPLES

DISCLAIMER

The challenges below are only examples meant to inspire you rather than prescriptive project blueprints. They are *not* mandatory project topics nor do they represent expected difficulty.

Your team is encouraged to propose their own idea, simple or ambitious, related to digital twins in exoplanets, origins of life, or biosignatures. Please pick the scope that best fits your skills and interests. If anything is unclear, contact us at info@hack-4-sages.org or on our Slack channel.

Contents

What is a Digital Twin?

Over the past few decades, astronomy has shifted from asking "Do exoplanets exist?" to "What are these worlds like and could any of them support life?" Today we know thousands of exoplanets, ranging from hot gas giants to Earth-sized rocky planets. However, discovering a planet is only the first step. To understand whether it might be habitable, scientists combine physics, climate science, planetary geology, and astronomy.

One emerging tool is the digital twin: a virtual copy of a real system that we can experiment with. On Earth, digital twins of the climate help us study extreme weather, sea-level rise, and long-term climate change. For exoplanets, we rely on physics-based models, simulations, and whatever data telescopes can provide (e.g., radius, mass, orbital distance, atmospheric spectra).

Even a very simple digital twin can help answer big questions:

- What would a planet's climate look like under different stellar conditions?
- How do oceans, atmospheres, or orbital motions influence habitability?
- Under what conditions could life emerge—or be detectable?

Digital Twins in the three Hackathon Categories

This hackathon focuses on three major themes:

1. Origins of Life
2. Life Detection and Biosignatures
3. Exoplanet Habitability

You do **not** need prior experience in exoplanet science to build such a model in this hackathon. A digital twin can be as simple as a few equations, a data-filtering tool, or a conceptual framework connecting different processes.

Each section below begins with a short overview to help you understand the main idea before seeing example challenge questions. You are encouraged to create your own version of a digital twin based on these general concepts.

1 Digital Twins in Origins of Life

Research on the origins of life aims to understand how physical and chemical processes can give rise to systems that are capable of metabolism, replication and evolution. Classic hypotheses include the RNA world, in which information storage and catalysis are combined in RNA molecules, as well as metabolism-first or lipid world scenarios that focus on chemical networks or self-assembling compartments. Candidate environments include hydrothermal vents, tidal pools, ice-covered oceans or impact-generated niches, each offering different gradients of energy, chemistry and confinement that might favour the emergence of life-like behaviour.

Digital twins here can be abstract (mathematical models of rare events) or environmental (simulating hydrothermal vents, tidal pools, impact environments). Students may model:

- probability of self-replication events
- long-term chemical cycles
- environmental fluctuations over time

This section gives broad conceptual prompts for building digital twins that explore how environmental conditions, simple chemical networks, or abstract processes can increase (or limit) the chance of life-like transitions. The emphasis here is on flexible modeling: you can build highly abstract probabilistic models, spatial agent-based systems, or more chemically detailed reaction–transport simulations.

1.1 Modeling primordial chemistry in an OoL scenario of choice

THEORETICALLY-BASED

Hydrothermal vents are among the most promising environments for the origin of life, providing natural chemical gradients, catalytic minerals, and thermal energy that could have driven early metabolic-like reactions. Understanding how these systems evolve over geological timescales offers insight into how prebiotic chemistry could transition into biology. Early Earth environments (vents, tidal pools, ice worlds) involve interacting thermal, chemical, and mineral processes. Conceptualize how you could computationally model a hydrothermal vent system and propose how it could be simulated efficiently over millions of years. Identify the main variables, such as temperature, chemical gradients, and mineral reactions, and describe how they might influence each other over time. Finally, suggest a simple way to model these long-term changes in a digital-twin environment that captures both the physical and chemical evolution of the system.

The proposed presentation will outline the governing equations of a hydrothermal vent system and discuss how the system can be simulated efficiently over million-year timescales. It will identify key variables—including temperature, chemical gradients, and mineral reactions—and explain how these factors interact and influence each other over time. Finally, it will suggest a straightforward approach for modeling these long-term physical and chemical changes within a digital-twin environment.

1.2 Simulating the Emergence of Life

CODING-BASED

Code a simulation where, for your own simplified definition of Life, the average probability of the event ”Life emerging” increases exponentially as a function of the value of one parameter of the environment. The task has several components:

1. Choose a minimal and explicit definition of life, for example, the occurrence of at least one successful self-replicating event within a fixed time window. This avoids biochemical complexity while still capturing the idea of a rare transition to life-like behaviour.
2. Pick a single parameter x that characterises the environment, such as energy input to the environment, concentrations of some building block, temperature, area/volume of the environment, etc. This parameter will be varied across simulations.
3. Assume that life-forming events occur at a rate that increases exponentially with the chosen parameter. A simple formulation is a Poisson process with rate
$$\lambda(x) = k\, e^{ax},$$
where $a > 0$ and $k > 0$. The probability that at least one life event occurs during the simulation is then
$$P_{\text{life}}(x) = 1 - \exp[-\lambda(x)],$$
which rises steeply and approximately exponentially with increasing x.
4. For each value of x, run many independent simulations, draw life events according to the probability $P_{\text{life}}(x)$, and compute the fraction of simulations in which life appears. Plotting this fraction against x demonstrates the expected exponential increase in the average probability of life emerging.

The presentation should include a description of the simplified definition of life used, the environmental parameter chosen, and how the exponential dependence was implemented. Include plots showing the fraction of simulations in which life emerges as a function of the parameter x, highlighting the expected exponential trend. Additionally, provide a brief explanation of the simulation setup, the assumptions made, and any insights or patterns observed from varying the environmental parameter. Optionally, include a short code snippet or pseudocode to illustrate the simulation logic.

2 Digital Twins in Life Detection and Biosignatures

Life detection relies on identifying signals—gases, surface patterns, spectral features—that cannot easily be explained without biology. Digital twins helps test:

- What different biospheres would look like
- How climate interacts with life
- Whether certain signals could be produced abiotically

Projects here may simulate simplified ecosystems, detection probabilities, or planetary feedback loops.

2.1 Planetary Climate Feedbacks

Planetary climates are shaped by interacting feedback loops. Negative feedbacks, such as the carbonate–silicate cycle, stabilize the climate by regulating CO_2 on geological timescales. Positive feedbacks, such as the ice–albedo effect, can amplify cooling and trigger global glaciations. Water vapor and cloud feedbacks, as well as biological processes, also play key roles in planetary habitability. A feedback loop means that a change in one part of a planet's system can cause effects that either reduce (negative feedback) or enhance (positive feedback) the original change. For example, if a planet gets warmer, chemical weathering may remove more CO_2 from the air, cooling it back down (negative feedback). But if more ice forms and reflects sunlight, the planet can cool even more (positive feedback). These feedbacks interact to determine whether a planet stays habitable or becomes frozen or overheated. Choose 2-3 feedback mechanisms (e.g. carbonate-silicate weathering, ice-albedo, water vapor, clouds, biospheric effects). For each:

1. Explain how the feedback works and whether it stabilizes or destabilizes the climate.
2. Describe how the climate would respond to a perturbation (e.g. decreased stellar flux or increased CO_2 abundance) with and without that feedback.
3. Illustrate with diagrams or conceptual plots where possible.

The proposed presentation will include a comparison of the chosen feedbacks. Teams should clearly contrast scenarios with and without each feedback, and include simple diagrams to support their explanations. You can also write python codes for this. By completing this challenge, participants will strengthen their conceptual understanding of stabilizing versus amplifying climate processes. They will learn to explain feedback mechanisms clearly, evaluate their roles in planetary climate stability, and connect these ideas to the broader context of planetary habitability.

2.2 Simulating Alien Life

CODING-BASED

All Life on Earth shares one ancestor: LUCA. We only know this LUCA-type of Life. But there could be many different types of Life in the universe. There could even be a different type of microscopic Life on Earth, not having LUCA as an ancestor, that we have not yet detected (the Shadow Biosphere!). It is possible that the type of an instance of Life influences how easy or hard it is for that Life to detect other Life of a different type, on another planet or even on the same planet. A digital twin can explore abstract "life types" and how they interact. Code a simulation where two life-types have different probabilities of detecting each other. This can be:

- A grid-based simulation
- A probability network
- A rule-based interaction model

The goal is to explore detection asymmetry, not biological realism.

The proposed presentation will provide: (i) a description of the model and parameters, (ii) a short code notebook (or script) to reproduce results from related literature/papers, (iii) summary plots showing detection probability vs density/asymmetry, and (iv) a short discussion of implications and limitations.

3 Digital Twins in Exoplanet Habitability

Habitable exoplanets are planets that can maintain the surface conditions (pressure/temperature) that allow liquid water on the surface. But exoplanets differ wildly: some are Earth-like, others are Jupiter type, some are tidally locked, some covered by global oceans, others with thick atmospheres.

A digital twin in this context is a model, simple or detailed, that explores how temperature, radiation, water, or atmospheric composition behave on a world we cannot directly observe. Your project may involve:

- Handling exoplanet datasets
- Creating/Running 1D climate- or heat-balance models
- Exploring how one physical variable shapes habitability

None of the models below need to be perfect; they only need to simulate a *concept*.

3.1 Analysing the Habitable Zone Data of Exoplanets

CODING-BASED

Thousands of exoplanets have been discovered, and a growing number are Earth-sized or slightly larger rocky worlds. Not all planets within the stellar habitable zone (HZ) are actually habitable, but identifying candidates is a first step. A planet's radius, orbital distance, and the stellar flux it receives are the most basic indicators of whether it could sustain liquid water at the surface. Using a provided exoplanet dataset (e.g. from the NASA Exoplanet Archive), write a code to:

1. Filter for Earth-sized planets (0.5–1.5 $R_\oplus$).
2. Compute the stellar flux and equilibrium temperature:

$$T_{\text{eq}} = \left(\frac{S(1-A)}{4\sigma} \right)^{1/4},$$

   where A is an assumed albedo (e.g. 0.3).
3. Identify planets whose orbital flux places them within the conservative HZ of their star.
4. Rank candidates by Earth similarity (you are flexible with radius or any other parameter you choose).

The proposed presentation includes a table of the most promising HZ candidates with key parameters such as radius, stellar flux, equilibrium temperature, and host star type. At least one plot should be produced, for example planet radius versus incident flux with the HZ highlighted. Teams should also provide their analysis code and a short write-up discussing their results, assumptions, and limitations. By completing this exercise, you will gain experience handling astrophysical data, calculating basic metrics, and critically evaluating the uncertainties involved in identifying potentially habitable exoplanets.

3.2 Tidally Locked Planet

CODING-BASED

Many of the discovered exoplanets are tidally locked, meaning they rotate around their axis in the same time it takes to orbit their host star. One hemisphere is in eternal daylight, while the other remains in perpetual darkness. At first glance, this might suggest that the dayside would burn and the nightside would freeze. In reality, atmospheric circulation, winds, and oceans can redistribute heat, creating regions near the day-night boundary (terminator) that might be suitable for life. You can model a rocky tidally locked planet and simulate temperature and water distribution to study habitability. The task has several components:

1. Find the formula to estimate tidal locking time. Explain why most discovered exoplanets around low-mass stars are tidally locked. Discuss whether this implies that most planets in the Universe are tidally locked.
2. Using your tidal locking knowledge, identify the type of star near which an Earth-like planet would become tidally locked, yet still receive the same energy Earth receives today. Use the provided star dataset.
3. Create a rocky planet simulation with these parameters: Planet radius, Planet mass, Albedo, Atmosphere composition, Amount of water, Mean planet temperature. Assumptions: Synchronous rotation, Completely flat terrain, Water in three states: solid, liquid, gas.
4. Add star luminosity and distance to star parameter.
5. Implement a model to:

   (a) Simulate the evolution of temperature across the planet.
   (b) Simulate water transport between states and between longitudes/latitudes.
   (c) Allow querying temperature and water mass at specific coordinates.
6. For the set up,
   (a) Enter Earth-like parameters for the planet.
   (b) Use the star from Step 2.
   (c) Set the initial mean temperature of the planet to 15 °C.

The proposed presentation will include several key visual and analytical components. First, it will feature a plot showing how temperature evolves over time at four representative locations on the tidally locked planet: the North Pole, the equatorial point facing the star, the equatorial point on the nightside farthest from the star, and the equator at the day–night terminator. Additional figures will illustrate the evolution of the planet's total water inventory, separated into liquid, solid, and gaseous phases, allowing the viewer to track how water is redistributed under synchronous rotation. The presentation will also evaluate whether the simulated climate reaches a steady state or continues to fluctuate over the modeled timescale. Finally, a dedicated habitability analysis will identify surface regions that simultaneously maintain temperatures between 0 °C and 100 °C and retain liquid water, and will track the fraction of total surface area that meets these habitability criteria as the system evolves.