Physics Hackathon 2020 – Project Ideas

If you're stumped trying to think up a project for the hackathon, here are some ideas for inspiration! Having trouble putting your ideas into code? Chat with other hackers or message a mentor and ask them for advice! We also strongly recommend that you take a look at some examples from previous years to get an idea what kind of projects you could work on:

- `physics-hackathon-2017-5733.devpost.com/submissions` [2017]
- `event.hackhub.com/event/3rdmcgillphysicshackathon/teams/submissions` [2018]
- `mcgill-physics-hackathon-2019.devpost.com/submissions` [2019]

One more remark: the following topics are intended for **main projects**. They are **distinct** from mini-coding challenges. For mini-coding challenges, stay tuned on the Discord server's #announcements channel, where they will be unveiled over the course of the Hackathon. On the other hand, many of the mini-coding challenges could be turned into main projects!

Contents

Part I
New Projects

1 Disproving the Flat Earth Conspiracy

Physics Concepts:

- Various!

Prerequisites:

- Trigonometry, High School or CEGEP physics

1.1 Introduction

The Flat Earth movement has gained a lot of attention in the past few years due to the rise of the internet. Numerous flat earth models have emerged from this movement and many experiments have been developed to prove that the Earth is not a sphere (or an oblate spheroid).

1.2 Goal

Prove them wrong either by simulating phenomena on a Flat Earth or designing a creative way of proving that the Earth is not flat! Below are a few ideas, but there are many ways to approach this problem.

- Simulate the climate of a Flat Earth. Can the atmosphere circulate without the Coriolis force?
- How do seasons work?
- How do stars move in the sky on a Flat Earth?
- Calculate the shortest airplane route and travel time on a Flat Earth. Does it match with the trajectories of flights in the real world?

---

2 Super-Resolution Astronomical Images

Physics Concepts:

- Various!

Prerequisites:

- Some knowledge of image processing

2.1 Introduction

Both ground-based and space-based telescopes have allowed astronomers to obtain images of objects as distant as 10 billion light-years away. For these extremely distant sources, these images are often very pixelated or low-resolution.

2.2 Goal

Use machine learning and/or computer vision techniques to generate high-fidelity, high-resolution images from low-resolution images.

---

3 Make Special Relativity Less Confusing

Physics Concepts:

- Special relativity

Prerequisites:

- None!

3.1 Introduction

Even though the math is relatively simple (and much simpler than general relativity!), even physicists can get mixed up when thinking about special relativity.

3.2 Goal

Make an animation of an event or events of your choice, in different reference frames, showing the effects of special relativity.

---

4 Exoplanets and Stellar Wobble

Physics Concepts:

- Kepler's laws of planetary motion

Prerequisites:

- Mechanics

4.1 Introduction

In 2019, the Nobel prize in physics was partially awarded for the discovery of the first exoplanet around a Sun-like star using the radial velocity method. As a planet orbits around its host star, the star wobbles because the planet is "tugging" on it. If the inclination of this planet-star system is right, the star will periodically move towards and away from us and its color will be blueshifted and redshifted, respectively.

4.2 Goal

Simulate this Doppler shift given an arbitrary planet!

---

5 CSI: Astronomy

Physics Concepts:

- Kepler's laws of planetary motion

Prerequisites:

- Mechanics

5.1 Introduction

A student at the University of Washington hit the jackpot when he picked up a call from the state police department. The police were investigating a crime and needed an astronomer to help them solve a case. They had photos taken by the criminal on the night of the crime, but did not know when and where the images were taken.

5.2 Goal

Identify the date, time, and location based on a photo of the night sky!

---

6 Circular Wave Pool

Physics Concepts:

- Interference

Prerequisites:

- Wave mechanics

6.1 Introduction

A surprising interference pattern of liquids becomes obvious in a circular pool (`https://www.youtube.com/watch?v=dCSqEG7gaIQ`). This effect is visible, and almost equally striking, when dropping a round object in a circular bath such as a large pot. Try this yourself next time you're doing the dishes!

6.2 Goal

Simulate this phenomenon!

---

7 Observing Elementary Particles

Physics Concepts:

- Particle physics
- Statistics

Prerequisites:

- Elementary knowledge of particle physics

7.1 Introduction

The ATLAS and CMS experiments at CERN have made some of their data available online, so that anyone can look for elementary particles! You can get started by following this tutorial: `http://opendata.cern.ch/record/50`

7.2 Goal

Understand how observations are made in particle physics. Choose a process you would like to observe in the data and differentiate background from signal events. You will need to understand what particles can be observed in the detectors, which particles are unstable and how they decay into other particles. Can you observe:

- The Z boson in data?
- The W boson in data?
- Top quark pair production?

---

8 Snowball Earth

Physics Concepts:

- Climatology
- Energy conservation

Prerequisites:

- High School or CEGEP physics

8.1 Introduction

The Snowball Earth hypothesis proposes that Earth's surface became entirely frozen at least once it its history. One of the main arguments opposing this hypothesis is the difficulty of escaping an all-frozen condition. Could the Earth have been completely frozen at some point in its past? Create a climate model to find out!

8.2 Goal

Create an elementary climate model to understand climate instability and feedback loops by studying the Snowball Earth hypothesis.

- You can start with a simple energy balance model as given here: `https://www.shodor.org/master/environmental/general/energy/index.html`
- Can you reproduce Aron Faegre's results? How many stable climates can you get? `https://journals.ametsoc.org/doi/pdf/10.1175/1520-0450%281972%29011%3C0004%3AAIMOTE%3E2.0.CO%3B2`
- You can add accuracy to your model by adding in more feedback loops. Would they enable a Snowball Earth to return to our present climate?

---

9 Higgs Machine Learning Challenge

Physics Concepts:

- Particle physics

Prerequisites:

- Machine learning

9.1 Introduction

This is an advanced project for competitors with a solid background in machine learning. The goal is to identify the Higgs boson using machine learning techniques

9.2 Goal

The challenge was issued by CERN and the full description of the project can be found here: `http://opendata.cern.ch/record/328`

---

10 Explosive Fruits

Physics Concepts:

- Classical mechanics
- Aerodynamics

Prerequisites:

- High School or CEGEP physics

10.1 Introduction

Seed dispersal is a crucial phase of plant development, and some plants have evolved impressively efficient seed dispersion methods. One especially impressive example is the hairyflower wild petunia (*Ruellia ciliatiflora*, in the family *Acanthaceae*), which explosively launches its seeds at velocities of over 15 m/s!

10.2 Goal

Model and stimulate the propulsion of the hairyflower wild petunia's seeds to understand the aerodynamics of flat discs, the effects of drag on the seed's orientation, and the forces acting on a spinning top.

10.3 Resources

- `http://rsif.royalsocietypublishing.org/content/15/140/20170901`
- `https://www.nytimes.com/2018/03/09/science/hairyflower-wild-petunia-seeds.html`

---

11 A Light-Induced THz Photonic Crystal

Physics Concepts:

- **FILL THIS IN**

Prerequisites:

- **FILL THIS IN**

11.1 Introduction

A photonic crystal is a periodic modulation of an index of refraction in space. They have the property where there are certain energy gaps where light is forbidden to propagate. By illuminating a semiconductor with light, it is possible to change the index of refraction wherever the light shines. Patterning the illumination creates a light-induced photonic crystal that can be used to control another long wavelength pulse of light called a THz pulse.

11.2 Goal

Objectives:

- Understand how to propagate light numerically by using the Yee algorithm and the appropriate software for finite difference time domain calculations.
- Understand how light can change the index of refraction of a semiconductor.

- Set up numerical conditions to model a photonic crystal by inducing a periodic modulation of the index of refraction.
- Model pulse propagation and map the "photonic band structure" of this light-induced photonic crystal.
- **Bonus:** Explore dynamic switching of a photonic band structure by turning it on while the pulse is inside. Trap a photon!

---

12 Pattern Formation on Animals

Physics Concepts:

- Diffusion
- Chemical reactions

Prerequisites:

- Partial differential equations

12.1 Introduction

Animals of all shapes and sizes can exhibit beautiful and incredibly varied patterns on their skin (snakes, frogs), scales (zebrafish, tropical fish), wings (butterflies, lady bugs), coat (big cats, zebras, giraffes), and more. Such patterns have developed over time due to evolutionary forces. Remarkably, the presence of these diverse patterns across many species can be explained by simple reaction-diffusion models, first proposed by Alan Turing in 1952.

12.2 Goal

Simulate the pattern formation of your favorite animal.

- Start by setting up the relevant partial differential equations and solving them in space and time.
- Explore different initial conditions.
- Explore different parameter regimes and the corresponding patterns. Can you generate the patterns that match a given animal?

12.3 Resources

- `http://science.sciencemag.org/content/sci/329/5999/1616.full.pdf`

---

13 Nuclear Radiation

Physics Concepts:

- Diffusion
- Climate
- Decay and half-life

Prerequisites:

- Partial differential equations

13.1 Introduction

The tsunami resulting from the 2011 earthquake in Tōhoku, Japan (magnitude 9.1 on the Richter scale) caused several nuclear accidents, most notably the meltdown of reactors in the Fukushima Daiichi Nuclear Power Plant. Radiation levels inside and outside the plant shot up to alarming rates. Even now, 7 years after the event, radiation is up, as can be seen on `http://safecast.org/tilemap/`. Why is all of this radiation still there?

13.2 Goal

The goal of the project is to recreate the Fukushima event via diffusion, winds and decay of radioactive nuclei given a source of radiation. To what extent can you retrieve the current radiation patterns? Consider adding the following variables into your model:

- Prevailing winds
- Rain
- Source strength
- Radiation

Which variables do you need to take such patterns into account? How strongly does each of these influence the current radiation patterns? Are there any other events whose aftermath you can simulate?

---

14 Grow a Crystal

Physics Concepts:

- Phase transitions
- Diffusion

Prerequisites:

- Solid state physics
- Partial differential equations
- Numerical methods

14.1 Introduction

Crystals exist in all shapes and are made up of diverse materials such as ice, rock, salt, metal, and so forth. Fascinating patterns are generated when atoms become arranged in such an orderly "crystalline" fashion. However, growing crystals is a tough job, both experimentally and computationally. Even with modern computing resources, it is incredibly difficult to simulate the growth of the simplest ice crystals.

14.2 Goal

Simulate the growth of a crystal. As this is a computationally advanced project, we encourage you to seek help from Professor Nikolas Provatas, whose grows crystals on computers as his job and who co-authored the introductory text below.

14.3 Resources

- `http://www.physics.mcgill.ca/~provatas/papers/Phase_Field_Methods_text.pdf`

Part II
Past Projects

---

15 Gravitational Lensing and Ray-Tracing

Physics Concepts:

- General relativity

Prerequisites:

- CEGEP physics, rough understanding of relativity

15.1 Introduction

According to Albert Einstein's theory of general relativity, which has survived almost a century of intense experimental testing, mass bends the fabric of space-time. Like all objects, rays of light travel in this space-time, and so their path can be affected by this distortion of space-time. A **gravitational lens** is a distribution of matter (such as a cluster of galaxies) between a distant light source and an observer which is capable of bending the light as it travels from the source to the observer. This effect is known as gravitational lensing, and the amount of bending is one of the predictions of general relativity.

15.2 Goal

Try to explain this phenomenon visually.

- Make a 3D visualization of the trajectory of rays emitted by a source (e.g. a star), given some nearby distribution of mass.
- Generate images of strong gravitational lensing!

15.3 Sample outcome

This project inspired a team at the 2019 Edition of the Hackathon. See the result here: `https://devpost.com/software/gravitational-lensing-a-simple-simulation`.

16 Fidget Spinners

Physics Concepts:

- Angular momentum
- Rotational energy

Prerequisites:

- High School or CEGEP physics

16.1 Introduction

Considered to be fun and relaxing, or annoying and useless, or everything in between, fidget spinners are ubiquitous. Some claim that they can treat anxiety or even improve mental focus (great for hackathons?) Regardless, we would like to better understand how these curious devices work.
When struck, they continue spinning in the same direction for a long time because the ball bearing in the center reduces the friction between the body of the fidget spinner and its central axis. The ball bearings on the sides however are there just to add more weight.

16.2 Goal

Design a fidget spinner simulation or app. It can be as elaborate or simple as you like. Here is a list of things you could consider including in your simulation or simply use as inspiration. Remember, these are just suggestions.

- Create a virtual fidget spinner app that's fun, fidgety, and educational.
- Make your simulation 3D and include all the gyroscopic forces.

---

17 Impressing Your Dinner Guests

Physics Concepts:

- Thermodynamics
- Heat transfer, convection

Prerequisites:

- Differential equations

17.1 Introduction

Your butcher claims that you should cook a roast beef in an oven for 15 minutes per pound of flesh. Is this scaling law plausible?

17.2 Goal

Design a simulation that calculates the ideal temperature and cooking time for cooking food items. For example, searing a steak, baking a sweet potato, barbecuing a sausage and so on. Make approximations and assumptions as necessary. In your simulation, we suggest you adopt the following definition of "cooked":

1. The center of the food item is at a certain temperature
2. The rest of item is as close to this temperature as possible (i.e. "uniform doneness")

Your simulation should take into account the shape, type, and weight of the food item in question. Here are some suggestions of features for inspiration:

- Very low cooking temperatures for very long times are not recommended because the meat may not heat fast enough to stop bacteria from growing. Can you impose this as a restriction in your simulation?
- Suppose your food item is irregularly shaped. Can you import the precise shape using a 3D scanner and feed that into your simulation? (This could actually be very useful for other project ideas!)

17.3 Sample outcome

This project inspired a team at the 2019 Edition of the Hackathon. See the result here: `https://devpost.com/software/mathter-chefs`.

---

18 Random Walk

Physics Concepts:

- Diffusion

Prerequisites:

- None!

18.1 Introduction

Random walk simulations are important for modelling phenomena in many fields of science. In population genetics, random walk describes the statistical properties of genetic drift. In physics, random walks are used as simplified models of physical Brownian motion and diffusion such as the random movement of molecules in liquids and gases. In mathematical ecology, random walks are used to describe individual animal movements, to empirically support processes of biodiffusion, and occasionally to model population dynamics. In brain research, random walks and reinforced random walks are used to model cascades of neuron firing in the brain. Can you model a physical phenomenon using a random walk simulation?

18.2 Goal

Design a random walk simulation that models or predicts a natural phenomenon. For example, you could model a drop of food coloring that is injected in the center of a cup of water. How long does it take for all the water to appear the color of the dye? Can you visualize your simulation in a nice way?

- Easy: Suppose a particle can only move left or right. If at every moment of time it chooses randomly which direction to go, and moves the same distance each step, what would its position look like as time passed? Make a graph of its position over time.

- Medium: Make the random walk simulation as in challenge 1. Run the simulation many times. Calculate the average position of the particle over all the different trials.
- Hard: Simulate a drop of food coloring that is injected in the center of a cup of water. How long does it take for all the water to appear the color of the dye?

---

19 The End of the World (As We Know It)

Physics Concepts:

- High School or CEGEP physics

Prerequisites:

- None!

19.1 Introduction

A meteor of the same energy as the one that caused the extinction of the dinosaurs is approaching planet earth. Luckily, we detect it in advance. You are asked to design a countermeasure.

19.2 Goal

Explore the many possibilities humanity has to deal with a situation like this. Write a simulation or simulations to see which of these approaches are plausible. Plot the trajectory of the asteroid with and without the countermeasure. Here are some ideas:

- Gravity tractor: Drive a heavy spaceship (or a spaceship towing another asteroid) by the incoming asteroid. Over time, the gravitational interaction should take the asteroid off course. How heavy do the space ships need to be and how long does it need to be near the asteroid for?
- Solar sails: Install solar sails on the asteroid and wait for the solar wind to push it off course. Plot the trajectory of the asteroid with and without the solar sails.
- Laser sublimation: Direct beams of concentrated light on asteroid. If it heats up, it will spew jets of debris and gas and change its course.

---

20 Planetary Motion

Physics Concepts:

- Basic mechanics

Prerequisites:

- None!

20.1 Introduction

In 2018, planetary motion simulations were a popular choice. Take a look at some submissions at `event.hackhub.com/event/3rdmcgillphysicshackathon/teams/submissions`.

20.2 Goal

Design a planetary motion simulation. Make it as elaborate as you like! You could do a simple solar system model or something more elaborate like calculating transfer orbits or modelling a space ship performing a gravity "slingshot" to get to Jupiter. Here are some things you might want to implement as features if you are looking for inspiration. Try to come up with your own!

- Calculate the interaction forces of an asteroid with different astronomical bodies and simulate its motion based on given initial position and speed. (You may choose to use just the 3 astronomical bodies that will have the greatest effect.) Can you find an initial condition which produces a stable orbit?
- Simulate a space ship's solar sails. How fast are they? How light does the material need to be for them to be plausible?

---

21 Trajectories

Physics Concepts:

- Projectile motion

Prerequisites:

- High School or CEGEP physics

21.1 Introduction

Can you come up with an interactive way to demonstrate the concepts of projectile motion?

21.2 Goal

Write a computer simulation of the trajectory of a projectile. Here are some ideas:

- Plot the trajectory of a ball depending on its initial velocity and the angle it was fired at.
- Make a game where the player has to move a box left and right to try to catch a ball that's launched at different angles.
- Make a game in which the player has to hit a target by adjusting the angle energy of the catapult.

22 Computer-Generated Art

Physics Concepts:

- Various!

Prerequisites:

- None!

22.1 Introduction

In 2018, a computer algorithm analyzed all of Rembrandt's work to learn the Dutch master's style and technique, before re-creating it in a new painting. Similarly, Antony Gormley's Quantum Cloud sculpture in London was designed by a computer using a random walk algorithm. And computer-generated music of all genres can also be found all over YouTube!

22.2 Goal

Create a piece of computer-generated visual or musical art!

22.3 Resources

- `https://www.livescience.com/54364-computer-creates-new-rembrandt-painting.html`

---

23 Prototype Learning

Physics Concepts:

- Biophysics

Prerequisites:

- Machine learning

23.1 Introduction

Imperceptible perturbations can fool machine learning algorithms to misclassify samples, while the nonperturbed samples are accurately classified. These are called adversarial examples. In a recent paper published by one of the organizers (Thomas), it is shown that cellular decision-making can aid machine learning algorithms in making robust decisions via strong nonlinearities, leading to prototype learning.

23.2 Goal

Find out what prototype learning is good for. First, use a sufficiently strong nonlinear activation function (like a logarithm) to get a neural network where the learned weights are prototypes (memorized from the training set). Then, understand how the classification is done, and if it is favorable in any way, perhaps in relation to adversarial examples. See Krotov and Hopfield for another example of prototype learning. If you consider doing this project, you are encouraged to ask Thomas for specific approaches.

23.3 Resources

- `https://journals.aps.org/prx/abstract/10.1103/PhysRevX.9.031012`
- `https://papers.nips.cc/paper/6121-dense-associative-memory-for-pattern-recognition.pdf`