Interactive Tool for Understanding Gravity and the Formation of Solar Systems

Interactive visual tools are an effective way of helping students engage with a subject. Providing an intuitively understandable representation of a system, they enhance learning by combining different forms of information representations (text, visuals, and sometimes audio etc.) and inciting emotional responses. The effect is amplified when coupled with game-inspired mechanics such as pre-set goals and a sense of progression, inviting more emotional investment, and encouraging deep processing in order to solve problems using newly developed insights about the system. These factors were shown to provide a great benefit to the effectiveness of memorizing and internalizing information (Kosslyn, 2016)[1]. I believe that in this way we can also contribute to the appeal of the subjects of physics and astronomy to the general population, by making them associate the subjects with fun, emotional, exciting and impressive activities, compared to the current prevailing view of precise sciences being unintuitive and uninteresting.[2]

The tool I present is an agent-based simulation of stellar bodies acting according to Newton's laws of gravity. It provides a fun, visually attractive and informative demonstration of the behavior of an astronomic system under gravity, especially the formation of a solar system, and can help students understand the evolution of emergent properties and the significance of different parameters in the system.

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[1] #selflearning: Dean Kosslyn's paper discussed the concepts of "Dual Code" and "Emotion", describing the presentation of information in visual as well as verbal form, and in emotional circumstances, as beneficial for building memory. This model can also be considered as encouraging "Deep Processing" with a "Desirable Difficulty", when goals are set for the users.

[2] #connotation: Outside of phrasing sentences, connotation plays a very big role in our lives, training our "system 1" unconscious mind how to instinctively invoke emotion in response to different concepts. By changing these cognitive biases we can benefit physics and related subjects as a whole.

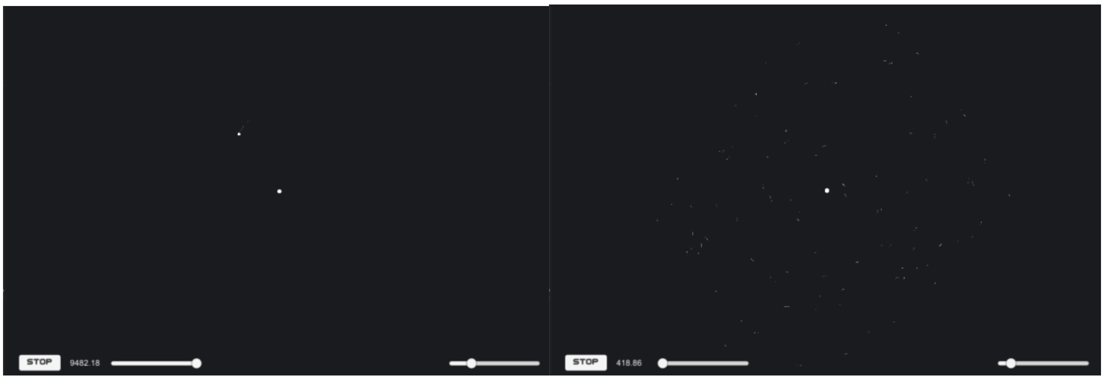

Figure 1. The states of a solar system before (right) and after (left) the bulk of the simulation. Out of a hundered bodies, only one stable orbiting planet remained.

Method of Simulation

The program creates a system comprised of a proto-star, and surrounded by randomly placed planetesimals with random velocities and random masses. The objects are then free to interact according to the Newtonian law of gravity:

$$F = \frac{Gm_1m_2}{r^2}$$

Where G is the gravitational constant, $m_{1,2}$ are the masses of any two objects and r is the distance between those two objects. A force F is then applied to both objects in inverse directions, toward each other, making them accelerate in an inverse proportion to their mass.

```
void FixedUpdate () {
    foreach (Rigidbody2D i in bodies)
    {
        float imass = i.mass;
        foreach (Rigidbody2D j in bodies)
        {
            if (i != j){
                Vector2 dir = new Vector2(j.gameObject.transform.position.x - i.gameObject.transform.position.x,
                                          j.gameObject.transform.position.y - i.gameObject.transform.position.y);
                float jmass = j.mass;
                i.AddForce(G * imass * jmass * dir.normalized / dir.sqrMagnitude);
            }
        }
    }
```

Figure 2. Code snippet demonstrating the implementation of Newton's law of gravity. Each frame, each object recieves a force calculated by the equation.

The simulation is done in time steps using the Euler method, in which the position, velocity and acceleration of any object are determined by their values during the last step, increased by a factor proportional to the duration of the time step.[3]

When two objects collide, they have a set probability to bounce off of each other or merge their masses and momentums. These are the only mechanisms necessary to demonstrate the processes involved in a formation of a solar system.

For reasons of practicality and simplicity, true-to-life scale was abandoned, otherwise objects would be very small relative to distances between them. As a result, the units used are arbitrary. I believe that this does not impair the tool's effectiveness in illustrating the essential gravity-related mechanisms of solar system formation. Also, objects have a singular density, such that their mass is directly proportional to their area, for easy assessment by eye. The simulation was constricted to two dimensions to optimize the performance of the system and to enhance visual clarity. Since angular momentum that remains from the initial formation of each system generally produces disk-like mass distribution, not much information is lost.[4]

Educational Value

Starting from a random dispersed population of planetesimals, each object interacts with every other object according to gravity. Over time, movement patterns arise[5]:

Planetesimals with slow initial velocities for example, especially massive ones, plummet down and merge into the star, while others have enough velocity to escape altogether and reach the border of the simulation. The ones that have just enough velocity to miss the star whenever they plummet, form orbits. Some orbits are usually made stable for a very long duration, visually

[3] #algorithms: Like any computer system, the program makes all physics and graphics calculation in time steps and not continually. The frequency of these steps was optimized to allow for a smooth but accurate simulation.
[4] #simulation: Any simulation is necessarily a simplification of the real system. Gravitational interactions in particular are a very good subject for simulation, since their salient features are simple, few and well-understood, allowing for accurate assertions and a lot of room for simplification.
[5] #emergentproperties: This simulation is an exploration of a complex system of interacting agents, and its strength is in demonstrating the appearance of emergent properties. All examples below arose spontaneously from initial parameters and consistent rules.

demonstrating the concept of gravitational circular motion. Collisions with other bodies, or even effects of their gravitation, can knock even the most stable of objects out of its trajectory and into the belly of the star.

Parameters have very significant effects on these patterns. For example, a wide range of planetesimal masses encourages the spontaneous appearance of moons, when a smaller object is entrapped in the gravitational field of another and starts orbiting it instead of the star.

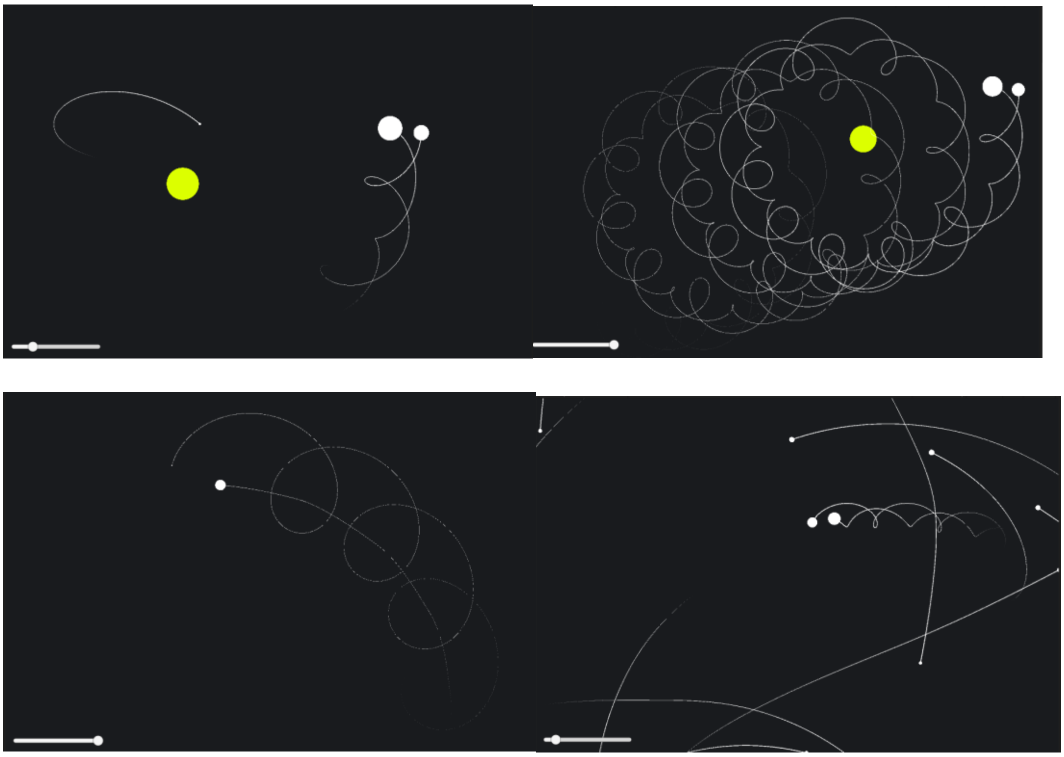

Figure 3. Exmples of moons sponteneously generated by the system. The bigger the mass difference between a planet and a moon, the more stable the system and the planet's orbit.

When the star is allowed to move along with the planets, a very interesting special case of a moon pattern can arise: A binary system, with two massive objects orbiting each other and the rest orbiting their combined center of mass. According to current scientific estimations, over half of all stars in the universe are a part of a multi-star system, and yet the concept is hard to understand intuitively without visual tools.

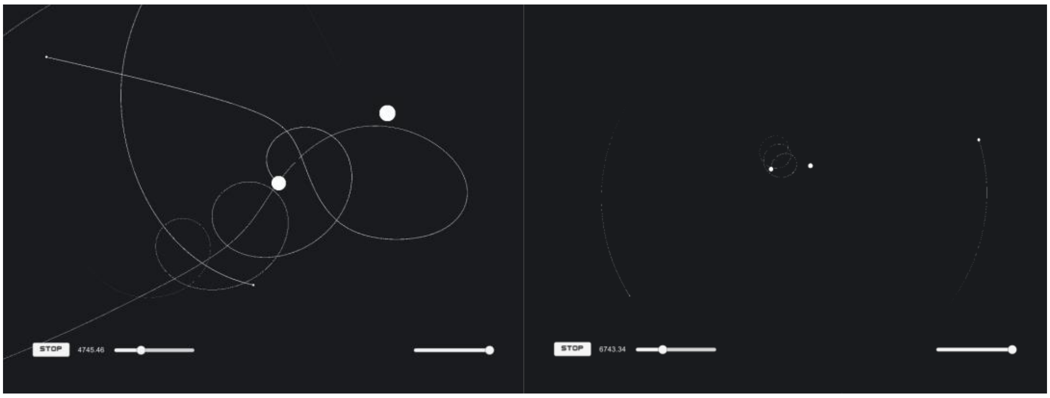

Figure 4. A binary system spontaneously formed by the simulation. Planets can follow 8-shaped orbits in this kind of a system, as demonstrated briefly on the left.

After a while, merging whittles down the planetesimals, consistently leaving only the most stable formations to stand, after having cleared their orbit of obstacles. This represents a final state for the solar system – containing several distinct orbiting bodies with optional moon, like our own[6].

Steps for Improvement

First of all, it's important to state that this model might be more appealing to some than to others. A mathematical computer model is not the only solution for visualizing gravity: physical models can be build, for example, out of lycra and simulated using ball weights, using real the third dimension to visualize the curvature mass applies to the fabric of space (PTSOS, 2012). But I believe I used the strengths of computer simulation to be able to precisely control different variables as well as simulation speed, and to visualize additional information such as trajectories.[7]

I kept in mind that the tool is designed to be used by students or people unfamiliar with physics concepts, so I tried to simplify the aesthetic. This ultimately might hurt the visual appeal that is

[6] #systemdynamics: One of the aims of the simulation is to show that the very nature of the system leads it to a stable state similar to our solar systems. This can be seen as an attractor, influencing systems with varying initial parameters. Nevertheless, some extreme modifications, such as intense initial velocities or a great gravitational constant, can lead to a shift and result in a system with no stable orbits at all.

[7] #modeltypes: The strengths of a physical model are in its clarity and precise calculation, but a computer model allows for more control of variables, and for an easier execution.

so integral to the aim of drawing the attention of the audience. A more diverse team of developers can improve this aspect of the tool.[8]

Besides allowing for more precise alterations of the initial conditions and better display of additional information, I believe the most salient improvement in the educational capacity of the simulation would come from gamification. For example, incorporating goals and level progression (such as: "Create a system with at least 4 stable orbits" or "Make a planetesimal reach terminal velocity and escape the simulation area!") will provide students with:

1. Incentive to keep using the tool and exploring gravity for longer.
2. Encouragement to process the information and gain insights about gravity that they could use to solve puzzles.
3. Emotional involvement that can enhance concentration and memory retention.

I believe this kind of simulation could be a very strong tool for getting people excited about astronomy, physics and complex systems as well as for enhancing students' understanding of related concepts.[9]

Description and Links

<u>The input parameters the program accepts are the following:</u>

1. Star
    a. Mass: the initial mass of the star.
    b. Fixed Position: whether the star can move or not. Moving enhances realism (allowing for binary systems, for example), but trajectories are less meaningful when not centered around a single point.
2. Planetoids
    a. Initial Amount: initial amount of planetesimals generated around the star.

[8] #audience: This tool is not intended to be used by professors to predict orbits. It was made for the general population and for students, which value the general representation of phenomena and visual impressiveness.

[9] #selflearning: cont.

b. Distance Range: the minimum and maximum distance for placement of planetesimals from the center of the star.
c. Mass Range: the minimum and maximum mass of planetesimals.
d. Velocity Range: the minimum and maximum mass of planetesimals.
e. Max Angular Deviation: planetesimals have velocities tangent to the radius of the distance from the star. This parameter allows for slight direction deviations.
f. Bidirectionality: in the formation of a solar-system, average angular momentum makes most planetesimals revolve around the proto-star in the same direction. This parameter allows for a proportion of the planetesimals to revolve in a reverse direction instead.

3. Global
    a. Gravitational Constant: Represents G in the gravity equation. The bigger it is the stronger the overall gravitational attraction.
    b. Merge Cross Section: The probability of each collision resulting in a merger of the two objects.

Links to download program:

Windows (recommended) :

https://www.dropbox.com/s/8my6shrazh2zzz7/1.0%20Win.zip?dl=0

MacOS:

https://www.dropbox.com/s/byp66b9jsul1gla/1.0%20Mac.zip?dl=0

Unzip the file and execute the program.

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