Interactive Large Structure N-Body Gravity Simulation for Immersive Learning in Virtual Reality

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Abstract. In this paper, we discuss our development and implementation of an Interactive Virtual Reality Application for Immersive Learning that simulates large stellar structure interaction. In contrary to conservative learning material, stellar structure dynamics can be understood effectively with our approach. We identified two major sub-topics, gravitational n-body interaction and the exponential decrease of the gravitational force, which non-interactive learning material cannot cover sufficiently and discuss the advantages of an interactive VR simulation. We tested a group of undergraduate students and investigated their skills regarding large stellar objects interaction prior and subsequently to the VR experience. Our studies have shown, that our immersive and interactive approach significantly adds to one's perception of Newton mechanics on large scale stellar bodies.

Keywords: N - body simulation, galaxy collision, stellar objects, gravity, VR

1 Introduction and goals

Real time n-body simulations[1] of large stellar objects like star clusters, galaxies, or objects that gravitationally interact on stellar magnitude such as black holes or quasars for virtual reality immersive learning[2,3,4,5] have recently become of higher interest due to technological advances and are challenging on several levels.

Large stellar object interaction follows gravitation with a chaotic, friction free trajectory of n-bodies[6]. To identify the mechanics for a deeper understanding, we separated it into two sub-topics: The exponential decrease of the gravitational force and n-body interaction in space. Conservative learning material such as books or movies do not provide an interactive user experiences. Written learning material cannot sufficiently display the developing of large stellar body events, due to the necessarily of having several time

adfa, p. 1, 2011.

frames to see the trajectories and their gravitational interaction. Movies on the other side cannot provide a sense of scaling on dynamic systems due to non-interactivity: Since the gravitational force is decreasing with the square of the distance, but is also depending on the mass of the objects, local clustering is possible and such cluster interact as small closed environment inside a bigger structure. A movie does not suffice in providing the experience in understanding these local and global effects, because the user cannot investigate interactively on local and global scale, but is rather bounded to the direction of the movie creator. In an interactive environment, a user would be able to implement new objects of mass in a running simulation and can observe its behavior on the local objects as well as in relation to the whole global system (all n-bodies).

An interactive n-body simulation of large stellar objects follows chaotic rules for local objects due to the n-body problem[6]. Conclusions of events such as galaxy collisions are consequently different for each case. We concentrate on the understanding of local phenomena in a global environment as well as the stable states of large stellar structures, which tunes in in time. Consequently statements can only be qualitatively, not quantitatively. Quantitative learning outcomes must concentrate on large stellar objects as abstract singular entities, or on single star-planet interaction, not including an inner dynamic of an n-body system. Such quantitative approaches allow precise calculations of positions and impulse. We rather assess qualitative statements in understanding trajectories of n-bodies and developments of galaxy collisions on a local and global scale. Our tests on human participants take this into account.

Simulating the behavior of stellar objects requires effort in abstraction due to their gravitational interaction with all bodies of the universe, due the range of the gravitational force. Observing events of interest, such as galaxy collisions, a proper time scale[6] must be chosen. Providing an immersive and interactive experience, such as an n-body simulation must be effective in regards to real time capabilities for a virtual reality experience. Since the gravitational force weakens with the square-distance of two body of mass, rational approximations can be made to increase the simulation frame rate.

Observable stellar body activates can be star dynamics inside a galaxy and the resulting rotation speed around the galaxy center in decency of the distance, galaxy collisions and interactions with other stars or massive gravitational objects such as neutron stars or black holes. In order to understand

and experience the trajectory of the mass bodies, observations in real time take usually up to several millions of years, so frame-steps must be in respect to a reasonable time scale. The rotation speed of stars around galaxy centers became of high interest since it was found, that this speed is close to constant and appears independent of the distance to the center[7]. This is an indication of more mass being present in the galaxy than can be observed and is labeled under dark matter[8] due to its invisibility for conventional methods. Providing a slider for increasing the dark matter inside the galaxy body of the simulation can be a significant tool for understanding until the rotation curve (along the radius) matches the observed data. Recent simulations of galaxy collisions of two spiral galaxies lead to a qualitative explanations of known galaxy shapes[9], to be a result of such a collision. Given two spiral galaxies with 100 million stars in average, the task for the simulation is to provide results for each frame in real time. Stellar bodies of big mass like supermassive black holes have a strong impact on the dynamics of nearby galaxies[10] and letting a user experience to be able adding massive bodies into the simulation at any time and place increases the immersion and the learning outcome in understanding movements of big stellar objects.

2 Setup

2.1 Testing

We tested a group of undergraduate students from STEM fields prior and subsequently to the VR experience. To assess qualitative statements of the skills of the human participants, we provide four n-body scenarios prior and subsequently to the VR experience and note the progress, see fig. 1. We asked for drawing the anticipated trajectory of the mass points as arrows in the right picture of a, b) and c) and a possible stable end state in the left picture.

The purpose of this test series is to evaluate their pre-conditions and common sense regarding gravitational n-body systems. Test a) tells how much the subject believes friction to be of a factor and how the subject interpret the gravitational force. Test b) tells if the subject is familiar with steady orbits or anticipates such. Test c) tells how the participants interpret local and global gravitation due to the indirect proportion of mass versus distance and also if the concept of no friction and steady orbits is present. Test d) is a qualitative analysis how the result of a merging of galaxies is imagined. We quantified the result of the tests with following system: For each test, a maximum of 4 points can be reached. For test a), arrows indicating an implosion (2 point), no cluster end result with steady orbit (2 points). Test b) arrows indicating a steady orbit (2 points), end result positions similar to start condition (1 points), preserving the rotation (1 point). Test c) Ring structure gets warped toward the mass point M (1 point), all ring points follow (1 point) keeping elliptical orbits in the end result (2 points). Test d) end result is merged (1 point), end result is still rotating (1 point) and end result is not clustered into a small center area, but still a large structure (2 points).

After the VR experience, we repeated the questions. Finally, we asked the level of experience in large stellar object dynamics prior to the VR experience, how the participants evaluate the VR experience to have extended their knowledge as well as grade the level of immersion.

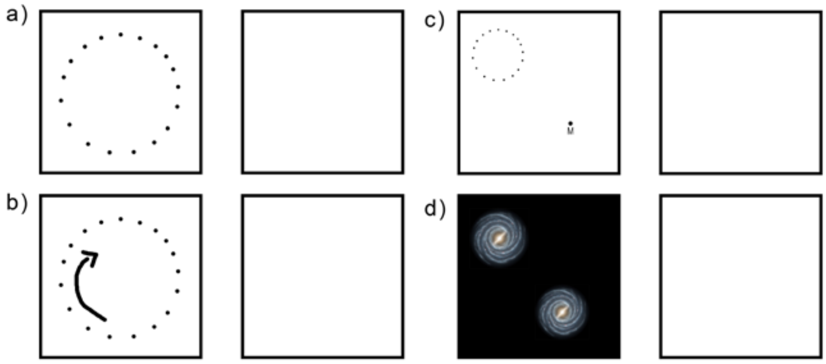

Fig. 1. Assessing the qualitative skills of gravitational n-body systems: a) several mass points of the same mass ordered in a ring structure without initial impulse. (b) The mass points similar to a) are rotating in a circle clockwise. (c) A mass point similar to a) with a mass greater than the whole ring structure is present. (d) Two spiral galaxies collide. We asked for drawing the anticipated trajectory of the mass points in the right picture of a, b) and c) and a stable end state in the left picture.

2.2 Hardware

For our approach, we are using Unity as platform, GPU compute shader for the simulation calculations, and VR Hero from VRgineers, a prototype 5K headset as well as an Oculus Rift for the VR experience. Our test run on an Intel i7 with 16GB and an NVidia GTX 1080 Ti graphic card.

3 System

3.1 Methodology

Our task was to simulate interactively single galaxies and its stars movement over time, galaxy collisions and adding/removing stellar objects with a high range selectable mass.

Our galaxy, the Milky Way, has in average number *n* = 10^{11} to 10^{12} million stars and is a spiral galaxy. Astronomy assumes that to be a typical representation of galaxies in the universe[11,12]. For galaxy collisions of two galaxies of approximately the same body, we have a lower boundary of $n = 2 \times 10^{11}$ stars.

Gravitational simulations must take all bodies of mass under consideration and consequently, without any approximations, all stars have to calculate the gravitational force to all other stars, resulting in an $O(n^2)$ algorithm. Since the gravitational force is decreasing with the square of the distance

$$F = G\,\frac{m_1 m_2}{r^2}$$

and not linear, we cannot sum up all masses and locations to a virtual average masspoint; *F* being the gravitational force, *G* the gravitational constant, $m_1 m_2$ the masses of the two interacting bodies and r the distance between them. Having $O(n^2)$ on 2×10^{11} stars leaves us with 4×10^{22} operations per frame and is far too much even for our system with 3840 shader units.

As discussed, the gravitational force is non-linear and consequently one cannot make cluster of mass points representing all stars of certain parts of a galaxy to reduce computational time, but the difference of calculating the gravitational force between a star and (a) a mass point or (b) all the stars represented by this masspoint is direct proportional correlated with the area of this cluster and the distance. The more distance between the star and the masspoint, the lesser the resulting error. Taking this under consideration, one would benefit greatly if the designated area of the event gets rasterized in three dimensions with several layers of resolution. Barnes and Hut[13] suggested a hierarchical approach by constructing an octree of a desired maximal resolution. Due to the computational time taken by constructing an octree on the GPU memory every frame as described by Laine and Tero[14], we decided to use buffers representing the 3D area and do the downsampling from higher resolution to lower in our code manually.

3.2 Algorithm

Every star is represented by mass (float), position (3 x float), impulse (3 x float) and an integer for having a linear list later to connect stars in one raster area, having 7 floats and one integer, 32 bytes in sum on a 32 bit system.

We have 7 raster buffers, see figure 1, where the highest resolution is 256^3 and every next buffer contains half the resolution of its predecessor: 128^3, 64^3, 32^3, 16^3, 8^3, 4^3. One buffer element contains the average mass and average position of the masspoint. Having 16 bytes for each masspoint, we need 33.5 MB for the highest resolution buffer, 4.2 MB for the second highest, and in sum 39 MB on the GPU memory for the whole hierarchical raster. To store a list of stars for later faster access of the local stars, the highest resolution buffer has 2 more integers, to hold the index of the actual star of the list as well as to the first star entering the list, needing in additional 17 MB for the first buffer.

Figure 2 shows our approach on an illustration of the Milky Way. The region gets subdivided into smaller areas.

First we loop over all stars and map their position into the highest resolution raster, adding their mass and position to the average variables of the raster buffer. If the star entering its values to the element of the buffer appears to be the first one, its writing its index to the “first star” and the “actual star” integer. If the “first star” integer already has an entry, its writing its own index to the star “next star” integer of the “actual star” and then overwrites it with its own index.

Then we downsample 8 elements of the buffer to its next lower resolution raster buffer element. Repeating that process for all raster buffer, we obtain masspoints in all different resolutions for the given space.

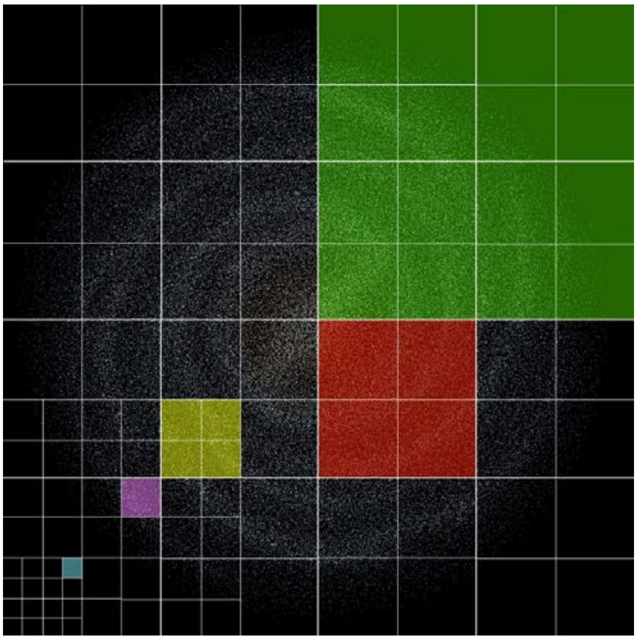

Fig. 2. We use a hierarchical raster buffer to store the average mass and position of the cluster of stars inside the raster elements on seven different levels of resolution, beginning with 256^3 elements, then 128^3 (cyan tile), 64^3 (purple tile), 32^3 (yellow tile), 16^3 (red tile), 8^3 (green tile), and 4^3 elements.

All our calculations take place on the GPU, having 3840 shader units working parallel on the algorithm.

To calculate the force on each star, we loop through all stars *k* in the local area of the highest resolution buffer, using the linked list we established. Then, we take all first resolution elements around the star (3 x 3 x 3 minus its own element) and repeat that process with the remaining 6 buffers, 3 x 3 x 3 - 1 operations for each, resulting in a sum of (3 x 3 x 3 - 1) x 7 + k which is in comparison with all stars of the given scenery a huge improvement.

If a star is too close to the border of the highest resolution rasterbuffer, it would only interact with the next masspoint, not with a possible close star. Such error can be corrected by increasing the amount of rasterbuffers to cover all border areas, but is subject to future implementation.

Still, 10^{11} stars are a huge computational problem, not only for computational time but also for the GPU memory. Even known dwarf galaxies such as NGC

5457 have a star amount of approximately 100 million stars, hence being problematic in real time as well.

We decided to reduce our galaxies to a maximum of one million stars, letting our stars represent small clusters of stars and believe this approach to still resemble real interaction of galaxies. With n = 10^6, we need 32 MB for the star buffer and have in average a local group of stars of k = 3 for one galaxy filling the entire simulation area.

3.3 Constructing the Galaxy

To construct a galaxy of stars, they need to be distributed according to observation (cluster galaxies, spiral galaxies, etc) and rotating around its center to satisfy

$$v_0 = \sqrt{G\frac{m_1 m_2}{r}}$$

which can be calculated once the positions are set, and v0 being the initial velocity in spiral direction, r the distance, G the gravitational constant and m1m2 the masses of the two stars. To have a realistic distribution, we developed a program to read from an image file and calculate possible star locations. Having a galaxy image see figure 2, we assume brighter areas to have a dense star population. Our algorithm takes the pixel brightness as well as the overall brightness of its surroundings into consideration to determine density, but also the thickness of the galaxy, see results in figure 3.

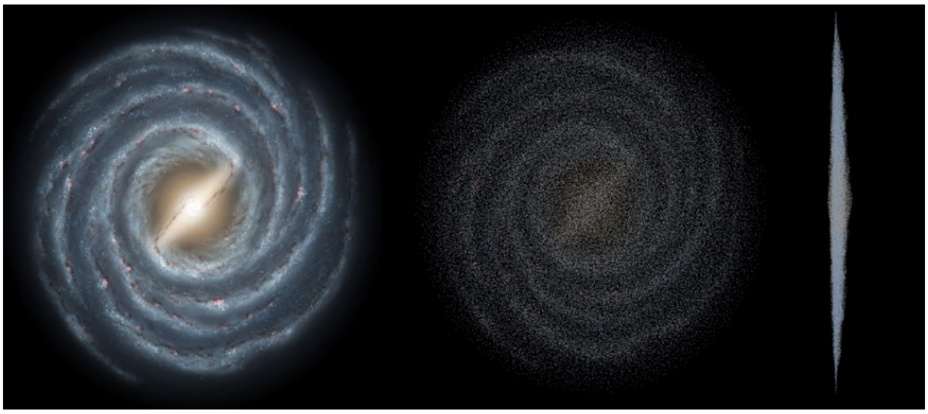

Fig. 3. On the left side an illustration of NGC 6814, scanned and after stars placed into position, the rendered 3D image of top down view is next to the right, followed by a side view of the galaxy.

4 Simulation Results

Our approach executes as timewarp and runs with a framerate of ~60 fps on an Oculus Rift. At program start, the user can choose between several scenarios involving different types of galaxies and collisions. Single galaxies or pairs of such for collision, galaxies which resembles real ones or hypothetical ones to increase the user experience such as pure spirals or rectangular shapes of star clusters.

Inside the scene, the simulation is paused by default and the user can start/stop the simulation any time or navigating through the scene. Additional stars can be inserted and the mass of this new stars can be selected up to the mass of supermassive black holes, which are represented by a dot to leave them visible for the user.

5 VR Experience

Our test participants were exposed to 4 different scenarios in the VR simulation, each of them in respect to the subject testing prior to the VR experience. The VR experience should challenge the perception the subject had prior and stated on the test.

In the first scenario, the user experiences a spiral galaxy with an initial impulse to preserve the rotation and in consequence the steady state. This initial impulse is slowed down and the galaxy implodes. Because there is no friction involved in space, as well as the dynamic of such an n-body system, the user experiences outer stars to be more accelerated to the center due to their distance to it, resulting in greater elliptical orbits. As a consequence, in time, after approximately 30 seconds, the galaxy spiral shape tunes in again.

We repeat the simulation of the first scenario in the second one. This time, the user is asked to place additional objects of high mass (up to 10 times the mass of all stars of the galaxies) into the simulation, observing the massive disturbance of the galaxy, but also witness the development of a new spiral galaxy with several cluster in their side arms due to local effects.

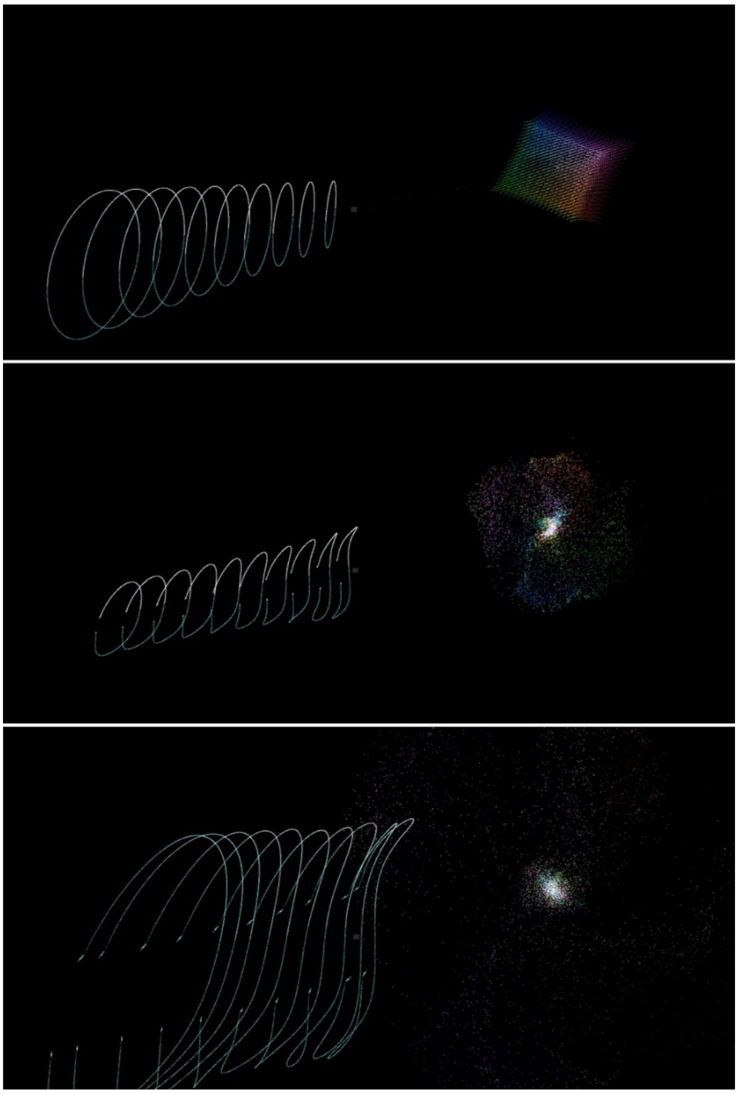

Fig. 4. Evolution of the simulation with 2 conceptual galaxies for better visualization in a two dimensional image, from top to bottom: In the first image, we see two conceptual galaxies, one being shaped as cube with stars having no impulse, the other one as several rings with different density and masses periodically over each ring. In the next image, we can see the uneven distribution of the rings start to take effect by splitting them up, while the cubed shaped galaxy implodes. Further on, in the third image, the rings bend towards the mass of the cube galaxy while the stars of the cubed one, which started to pass the center at the second image which high speed, are still expanding, though at the center a cluster of stars concentrate.

The third simulation merges two spiral galaxies and in time an elliptical shaped galaxy with two long side arms is formed. In the beginning the two center of the galaxies are still preserved, but ultimately merge into one. All of this stages can be observed in the real universe as a consequence of galaxy merging.

The forth simulation bring our subject into a test room, where we present conceptual galaxies, see figure. 4. The cube shaped galaxy consists of stars without impulse and as soon as the simulation starts, the cube implodes. Due to the lack of friction and the preserving of energy, steady orbits tune in in time. Stars from the outer region of the cube get more accelerated, resulting in a big elliptical orbit around the center. Due to n-body dynamics, a rotation is induced naturally and a spiral galaxy is formed.

6 Learning Experience Outcome

After the VR experience, we tested the subject again. The same questions we used prior to the simulation were taken again for testing. In table 1, we compare the prior to the subsequent testing as well as present three additional questions.

It is clear to see, that our testing group of n=41 had a wide spread (10 : max – min) set of initial skills. Comparing that with their own assessment, we found a bandwidth of 14 (max – min) with an average far below their prior testing. We interpret that difference as assessing their knowledge based on institutional learning experience for “question 1” versus common sense and base intelligence for the prior tests.

The effect of the VR experience is overwhelming positive. The subsequent testing resulted in a bandwidth of 4 (max - min), with an average gain of 3.2 nearly closing the gap to a maximum of 16 points. We interpret this result as a success in providing an interactive learning experience to enhance qualitative skills for large stellar object interaction.

n = 41	average	min	max
prior	12 (out of 16)	6	16
subsequent	15.2 (out of 16)	11	16
gain	3.2	0	8
Question 1	4.1 (out of 16)	0	14
Question 2	6.8 (out of 10)	1	10
Question 3	8.8 (out of 10)	6	10

Table 1. In this table we see the results of our testing prior and subsequently to the VR experience. The columns represent the average, minimum and maximum points for the tests. Row 1 represents the data prior to the VR experience and row 2 subsequently. Row 3 represents the gain of points comparing before/after the testing. The question of row 4 to 6 was: 1) My knowledge on galaxy dynamics prior to the VR experience was (0..16). 2) The VR experience extended my knowledge (0..10). 3) Evaluate the level of immersion of the VR experience (0..10). Following point system was taken: 0..absolut no/bad, 10 absolute yes/good. 41 human subject were tested.

Overall, the participants evaluated their gain of knowledge uniformly positive (question 2) and noted a highly immersive VR experience (question 3).

7 Conclusion and Future Work

In our work, we have shown that qualitative, immersive and interactive real time gravitational force simulation on large stellar structures in virtual reality have a significant positive learning impact. We have shown, that such simulations are possible under several approximations and abstractions on parallel algorithms for compute shader GPU. We provided a tool for constructing a galaxy from an image file and tested participants on the impact and learning outcome when interacting with our simulation, concluding that such immersive virtual reality experience has significant impact due to the nature of this field of study, being mostly taught in a static and abstract manner, given the time scale and complexity of this stellar events. There is room for further improvement to make the simulation more precise and effort will be made to include more stars per galaxy to match real galaxies in future. The next step is to implementing the Lorentz transformation in dependency of the speed of the user while traversing the simulation, in order to warp the perception of space according to relativity.

8 Acknowledgements

The equation to compute star movement and the text files with predefined galaxies were received from:
http://courses.cs.tamu.edu/sueda/CSCE441/2017S/labs/L17/

The following link was used to learn how to render particles in Unity using the compute shader: https://github.com/antoinefournier/XParticle

The following links were used to learn how compute shaders in Unity work: http://www.emersonshaffer.com/blog/2016/5/11/unity3d-compute-shader-introduction-tutorial, http://kylehalladay.com/blog/tutorial/2014/06/27/Compute-Shaders-Are-Nifty.html

The camera system was modeled in reference to the following link:
https://learnopengl.com/Getting-started/Camera

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