The Project:

Any word marked with a 1 can be found in the glossary with the corresponding entry.

Analysis:

Problem Definition:

It is currently difficult for teachers to teach about rigid1 and soft2 bodies. A lot of students struggle without a visual representation to understand what is happening, however, these visual representations are often limited to simple animations and aren’t customisable. This leads to situations where the student can see the visualisation but can’t understand what is happening it, the students are often even more confused as to what the teacher is trying to teach. When I spoke to a few of my piers about this problem, they agreed that visualising a problem helps them understand it. One of them commented that once he understood the types of problems that questions were asking he was fine, but had issues initially learning about them as he didn’t understand what the diagrams were representing.

The idea for my project is a 2D physics simulation that works together both rigidbody and softbody physics. This simulation will be completely customisable, allowing whoever is using it to set up a scene quickly, run it in real time, and customise a scene however they want. This will make it easier for teachers to teach their students with multiple examples, as well as allow the students to play around with the simulation themselves. A lot of students learn better with an example that they can tinker with to help them to understand what is happening in a specific example.

Why a Computational Solution is Suitable:

It is difficult to recreate a collision experiment at home, or on the fly. On the other hand, it is much easier to run an application on a computer. A simulation would also be able to make any calculations the student also has to do, this would allow them to check their results. All of the computations that a computer makes are also repeatable, meaning that the user could replay the simulation multiple times and get the same result, unlike real life where there are many unpredictable factors.

Stakeholders:

My program will be used to help both teachers and students teach and learn about the concepts of collisions3, rigidbodies and softbodies, therefore it makes sense that my shareholders are both. In order for the stakeholders to use the program effectively, it needs to be easy to pick up but also complex enough to be used in every collision system available. To make this possible, I will have multiple menus with different options available for different purposes, as well as a tutorial section so that new users can learn to use the program easily.

My stakeholders will be my friend Jack who both take physics and further maths, and my physics teacher [INSERT TEACHER HERE]. Both physics and further maths include sections in mechanics on collisions, and students from both subjects should be able to use the software without having to take the other. This means that some settings should be optional, as it might be covered it one subject but not another, or some should have multiple options for how to calculate, (eg energy methods vs suvat methods of motion).

As a student, Jack will be more focused on using the software for revision purposes as well as using it to understand the topics. [TEACHER] already understands all of the topics, instead, they are going to be using the software as a demonstration tool. Having both of them as my stakeholders will allow me to take feedback, and tailor the experience to both groups.

Interview:

Jack:

Q: How do you currently learn about collisions.

A: Depends on the subject, in further maths - I don’t think collisions are in normal maths – we mainly learn about the theory, we do a lot of calculations as well as draw diagrams to represent what is happening. In physics, we still do calculations, and diagrams, but physical examples are also used, we do some practicals on conservation of momentum and other things.

Q: Do you think that a computer program where you can simulate the system would be of any help to you while learning mechanics?

A: Yes, in maths we dive deeper into the theory, but I never get the chance to actually see the system in action. Even when doing physics, I can’t just set up a practical at home, so having a piece of software I can download and use anywhere would be very useful.

Q: What sort of features would you want to have available to you inside the simulation?

A: Being able to use different equations to model the same situation. Having a menu with all of the options in one place would mean that I could easily set up the scene. Also, being able to click on an object and change its properties.

Q: What kind of objects do you think should be in the simulation?

A: Particles, walls, some polygons, as well as hollow variations.

Q: What have you used in the past to help you understand the concepts?

A: Online videos and physical examples in physics. It is difficult in maths as we can’t set it up as a practical.

Q: What operating system do you use?

A: I use Linux when programming but I use Windows for school work, so I would want the application on Windows.

[INSERT TEACHER HERE]:  
Q: How do go about teaching collisions and mechanics?

A: I try to teach with a lot of practicals so that the students can actually see what is happening. After the students have finished the practicals, I generally link it to the theory and equation behind it. Depending on the topic, I try to get students to derive the equations themselves at A-Level. Showing them the equation and making them link it to the experiment they have just done works well.

Q: Do you think a simulation that you and your students could use would be useful?

A: At A-level, I try to get the students to do the experiments themselves, this is great inside the classroom but very difficult when they go off and do their own study on the subject, I am sure that a lot of my A-Level students would find this very useful for their own study. At GCSE, some of the topics are hard to do with the large class size and limited equipment, so I have to show them all the experiment rather than them do it themselves, repeating the experiment [In multiple lessons] takes a lot of time to set up, being able to just pull up a program with a pre-loaded scene would save a lot of time.

Q: What sort of features would you want to have available to you inside the simulation?

A: Being able to save and load scenes would be a massive time-saver, similarly, being able to send saves to others would let me set prep to students easier as well as send it round the science department. Also, being able to pause the simulation at any point and change what is happening.

Q: As a follow on would you want to be able to drag the objects in the simulation with a mouse during that pause time and when setting up the scene?

A: Yes, that would be good, but also having a window where you can set the details about the object like its velocity, it would be nice if it showed up when you clicked on the object.

Q: What kind of objects do you think should be in the simulation?

A: I think the most needed one is particles – just circles, these are used all the time to model situations. But also shapes such as rectangles, squares and lines. And you should be able to set whether an object is stationary or can move.

Q: What have you used in the past to help students understand the concepts?

A: A real life example works the best, but when that isn’t available, I often draw diagrams. PhET has a lot of really good simulations that simulate things like projectiles, however, some of their simulations haven’t got great interfaces, and you need to restart their simulation every time you want to change a variable.

Q: What operating system do you use?

At school, I use windows, I have an old Macbook at home, but I don’t use it for any work. I would want the program to run on Windows primarily.

Currently Existing Similar solutions:

PhET:

Overview:  
PhET is an organisation that provides “interactive simulations for science and math”, it has a website full of simulations, some that run with HTML5 (using JavaScript) and some with Java, and all of their source code is available on GitHub. They have a collision simulation called Collision Lab. This simulator has 4 modes, “Intro”, “Explore 1D”, “Explore 2D” and “Inelastic”, Intro is a 1D simulation (one that only has one dimension of movement, in this case left and right) that has no borders, this means that the balls just fly off the screen after they have collided. Explore 1D is very similar to intro, however, there are borders so that the particles rebound off the edge of the viewport to collide with each other again. Explore 2D is the same as Explore 1D, but as the name suggests, in 2 dimensions, the particles can now move up and down as well as left and right.

Positives:

* UI is very clean and self-explanatory.
* Ability to drag the balls and their velocities around is nice and makes it easy to quickly change the attributes.
* Different coloured and numbered balls makes it easy to distinguish between different balls.
* 2 different speeds available.
* Arrows to show the current velocity.
* Can change the elasticity of the collision.

Negatives:

* Limited to 4 balls at once, and no other shapes exist, however, this is enough to model the majority of simulations that occur at GCSE and A-Level.
* Difficult to input values. Eg, when setting the velocity of the object manually, a pop-up window appears to input the values, and the keyboard doesn’t input anything.
* Not very customisable.

What my stakeholders think:

Jack– I think PhET is a really good website with lots of good simulations, the collisions one is a little clunky, but pretty easy to use. I think that the arrows representing velocity is a nice touch.

[TEACHER 1] – I recommend PhET to my students, the collision simulation almost all that is needed to teach the simulations, I also like the ability to change the elasticity of the collisions for when we are teaching about elasticity.

What I can use:

I will use features such as the dragging of the balls and velocity vectors, these were easy to use and very useful, a definite include. Being able to customise what individual balls look like is a niche but nice feature which extends upon what they have done with the multicoloured balls here. I will also include the overlays such as the velocity of each ball and the momentum. I don’t use Javascript that much, so it will be difficult for me to adapt their collision mechanics into my own simulation, however, all of the source code is available on GitHub (<https://github.com/phetsims/collision-lab>).

Bubble chart

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The Physics Classroom:

Overview:

The Physics Classroom is a website with lots of helpful explanations and simulations covering the subject of physics. This website is very similar to PhET, but also has some more explanations and videos describing the topics. Like PhET, all the simulations are HTML5 based, so they all run in the web-browser. They also share some of the same ups and downs as PhET.

The collision simulator is very simple, a two cart system meant to mimic how an experiment would be set up in real life. You can control the mass and initial velocities of the two carts as well as if the collision is elastic or not.

Unfortunately, all of the options were too big to fit on any of the computer screens that I tried. However when I read their homepage, it said that the simulations were “Designed with tablets such as the iPad and with Chromebooks in mind”. Even though this allows the user to use these simulations on their tablets, it does detriment the use on a computer.

Positives:

* Simple to use interface
* Can change the collision type
* Easy reset button
* Shows velocity above cart

Negatives:

* Doesn’t fit on the screen (PC only)
* Not very customisable
* Can only use two carts

What my stakeholders think:

Jack – This simulation is OK, I don’t like how it doesn’t all fit on my laptop screen, but it does have a very easy to use interface. Also, some of the situations that I have to calculate involve more objects as well as in two dimensions, so it wouldn’t be suitable for those.

[TEACHER] – I wouldn’t use this simulation in the classroom. It doesn’t all fit on my screen, and doesn’t have any advantage over just setting up the simulation. I do like the elastic and inelastic collisions, but it would be nice to be able to have a scale for elasticity.

What I can use:

I can take the elasticity, but I would change it to be a value between 0 or 1 that the user can specify, maybe a slider that they can slide. I can also take the reset button to reset it to the last paused location.

Timeline

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Graphical user interface, application, chat or text message

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Features of the proposed solution:

Initial concept:

I will make a program that contains an easy-to-use GUI. This GUI will include a view window that shows the collisions, a drop-down menu with a list of all of the objects, when an object is clicked in the view window, it will bring up a menu that shows all of the object’s data, the user will be able to edit the values here, such as the mass of the object, to create custom scenarios. They will also be able to drag the objects around the view window, as well as pause the simulation and change the speed of the simulation.

The limitations of the proposed solution:  
The main limitation will be how quickly a user can set up a simulation, if it becomes too slow or difficult for them to simulate a situation, they won’t bother and resort to another method. One of the main things I should focus on is the speed of the application as well as creating a simple to use interface so that they can create setup their simulation faster.

Another limitation would be how I will only be simulating in 2D. Even though 3D simulations are a part of the specification for some subjects, I will not be simulating them here. This is because they will add another layer of complete that is not needed for the majority of subjects and exam boards. If you are doing calculations with 3D collisions, you should already have a strong foundation with 2D collisions so this shouldn’t be much of a problem.

Stakeholder Requirements:

|  |  |
| --- | --- |
| Stakeholder Requirement | Reason |
| Different types of objects | To simulate different unique situations, and for students to play around with |
| Simple interface | So that people only have to learn about how collisions work, not how to use the software as well |
| Able to pause the simulation at any time | So that teachers can explain things. |
| Doesn’t take lots of processing power | School computers are very slow, if they can’t run the program well, it can’t be used for that much teaching |
| Arrows representing velocity | So that users can easily see where the object is going, even when paused. |

General Requirements:

|  |  |  |
| --- | --- | --- |
| General Requirement | Reason | Difficulty |
| A particle collision system | This is the main function of the program, simulating particle collision. | Medium – Detecting the collisions of different types of objects will be the hard part. |
| Able to move objects by dragging them with the mouse. | So that the user can set up custom simulations that will demonstrate what they want to | Medium –translating mouse position to the simulation will be a challenge |
| Pause the simulation with a button | This can be used for multiple uses, such as explaining what just happened or making predictions while teaching | Easy - a simple if statement to check if the simulation is paused or not will do |
| Easy to use, clean interface. | Otherwise the program will be difficult to navigate and won’t be used to its full potential | Medium – Designing user interfaces can sometimes be a challenge |
| Multiple objects can be simulated at once | For simulating larger scenarios | Easy – having a container of objects should solve the problem |
| Multiple shapes and sizes can be used at the same time | To simulate multiple different scenarios | Medium/hard – its not the shapes that’s hard, its calculating the collisions for the shapes |
| Be save and load scenarios. | For fast setup for common scenarios | Easy - shouldn’t be difficult to store object info into files |
| Multiple simulation speeds | To slow down or speed up the collision for clarity or example | Easy - a variable that scales the dt in the simulation should solve the problem |
| Not computationally heavy | So that the slower computers can still run the program without any problems | Medium – efficiency is a challenge every computer program faces. |

Hardware/Software requirements:

These are general requirements that the user will have to have in order to run the final program.

|  |  |
| --- | --- |
| Requirement | Reason |
| A computer that runs Windows | The majority of users will run Windows, compiling the program for other OS wouldn’t be worth it. I don’t know of any schools that don’t run a version of Windows |
| Mouse and keyboard | To be able to navigate the interface |
| OpenGL compatible graphics card/processor | All of the graphics will be rendered in OpenGL. They will not show anything if it is not compatible. It should be noted, most graphics cards are compatible. |

Measurable Success Criteria:

|  |  |  |
| --- | --- | --- |
| Number | Criteria | How to evidence |
| 1 | Main window that contains the simulation | Screenshot of the window |
| 2 | Simulation detects collisions | Show the code that detects collisions as well as the tests |
| 3 | Simulation accurately simulates the collision, with real time collision detection and accurate collision maths that calculates post-collision velocity | Show the code, tests, and on screen data that shows before and after the collision, as well as hand done calculations on what should have occurred |
| 4 | A pause button that pauses the simulation when pressed. | A screenshot of the main window, as well as the code that shows how it pauses the simulation |
| 5 | Different object shapes and sizes, including: a circle, square, n-gon (a polygon with n sides) softbodies. | Screenshots of the different objects and sizes |
| 6 | Option that changes simulation speed (at least 3 speeds: slow, normal, fast) | Screenshot of the speed input as well as the code of how it works |
| 7 | Help option that describes how to use the program | Screenshot of the help screen |
| 8 | Able to drag objects with the mouse. | Series of screenshots that show how dragging works |
| 9 | A window that shows the object data when clicked on (such as mass, position, velocity etc.) | A screenshot of the window, showing the object data |
| 10 | Objects render to the view window correctly (in the correct position and in the correct shape) | A screenshot that shows objects |
| 11 | Arrows representing velocity render when option is clicked | A screenshot of the velocity arrows on and a screenshot of them off |
| 12 | Option to change the objects’ colours | A screenshot of the different colours |
| 13 | Simulation is fast | A screenshot of the framerate |

The game will be written in C++ and all of the GUI will be done using ImGui. Writing it in C++ will mean that the simulation will be extremely fast, however, it does mean that I will need to compile the code for any potential platforms. However, most schools use windows, this means that compiling for x86 windows should cover most use cases. If not, the code will be open source on GitHub, so anyone can recompile for their machine. ImGui is an open source GUI interface for C++, it is fast, and can be used with most graphics engines, including OpenGL, which is what I will be using.

Design:

Decomposing the Solution:

This involves splitting up the solution into more manageable modules. There will be three main modules: the simulation, the GUI, and utilities. The simulation will include anything to do with the maths, collisions, bodies, etc. The GUI will encompass all the interaction with the user, displaying the simulation and all of the menus. The utilities will involve all of the other small parts that don’t fit into any of the previous section, this includes saving and loading simulations, the options and others.

Chart, box and whisker chart

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// TODO: Diagram can be resized later

Collision detection:

Axis-Aligned Bounding Box (AABB):

AABB is a basic detection method that only works with rectangles whose edges are parallel to the axis. It works by comparing the positions and sizes of the 2 rectangles. A pseudocode example would look like:

function AABB(position1, position1, size1, size2){

return position1.x < position2.x + size2.width &&

position1.x + size2.width > position2.x &&

position1.y < position2.y + size2.height &&

position1.y + size1.height > position2.y);

}

Separating Axis Theorem (SAT):

The SAT is a collision detection method that uses vectors maths to project the objects onto a “separating axis” which then compares to find collisions. One major advantage of the SAT is that it works on any convex shape, this will be very helpful

The projection is done by finding a perpendicular line which passes through a vertex. The point where this line intersects the axis is the projected vertex, we call the projected vertices its shadow.

We compare both shapes’ shadow on the axis to check if they overlap. If they overlap on every axis, then the shapes have collided. The axis are the lines perpendicular to the faces of both shapes.

The pseudocode for SAT is below

function separatingAxisTheorem(object1, object2){

edges = object1.getEdges() + object2.getEdges()

axes = []

for edge in edges:

axes.append(perpendicular(edge))

for axis in axes:

projection1 = object1.project(axis)

projection2 = object2.project(axis)

if not overlapping(projection1, projection2):

return false

return true

}

I will be using the Separating Axis Theorem to detect collisions, as it allows for more complex shapes than just rectangles. However, when using SAT, there are 2 major of problems, it is computationally intensive and objects moving fast enough can just pass straight through each other (tunnelling).

The first problem can be minimised by using optimisation techniques, however, the second is harder to solve. One solution would be to check the collision at multiple times per frame, the problem with this solution it multiplies the number of computations by the number of checks per frame, doing this a lot would slow down the simulation, this would fail success criteria number 13. Another solution would be to have a speed limit for the simulation, while limiting the simulation, this would prevent all tunnelling. High speed collisions aren’t a part of any physics or maths curriculum, so this wouldn’t be a problem from a teaching/learning standpoint.

Softbodies:

Softbodies are notoriously difficult to simulate. They are incredibly computationally intensive and are known to break apart with a small force. There are multiple ways of simulating softbodies, but I will go with the Spring-Mass model.

This model uses springs connected to mass points to simulate the forces of the softbody. The force provided by the spring is given by F=kx where k is the spring constant and x is the extension. This provides the force both outwards when the spring is compressed and inwards when it is stretched. The extension can be calculated by subtracting the natural length of the spring from the distance between the two ends.

GUI:

The UI will use movable panels that hold different information, for instance, one panel will hold the data of the selected object, another will be the viewing window that shows the simulation. These can be dragged anywhere and ‘docked’ to the main window. Below is an example of what the app could look like (it will also be the default layout when the app first loads).

Table

Description automatically generated

Object Information Panel:

This panel will contain information of the focussed object. You can focus on an object by clicking on it, the user can defocus by clicking on empty space. The user will be able to change all of the information in the panel. It will contain things like the mass, the velocity, the position, the force exerted on the object etc. If nothing is focused, the panel will contain options to add a new object

General Information Panel:

This panel will contain information about the overall simulation such as the framerate, the number of objects currently being simulated etc.

ImGUI:

ImGUI is a GUI library for C++ that focuses on being simple and easy to set up, it is also extremely customisable which is what lead me to choose this as my GUI library. It is all open source and can be found on GitHub, they also contain some useful examples so that beginners can see how the code works and is put together. Below is one of the windows in the examples.

Graphical user interface, application

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And here is the code that creates this window.

Text

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As you can see, it is very simple to add new GUI elements. It also uses pointers to edit the variables. This code can be contained in a function, so it very easy to group the different windows.

It also contains functionality to draw directly onto the windows by passing in a FBO (frame buffer object) which leads me onto OpenGL

OpenGL:

OpenGL is the backend graphics engine that runs on the graphics cards. It passes buffers of data to the GPU which passes these buffers through shaders which ultimately produce either an output to the screen or a Frame Buffer Object which can be used to render to other non-default outputs. I will use abstraction to abstract some of the complex OpenGL methods into an easier to use Renderer class.

Key Classes and Functions:

This is an overview of the different classes that the simulation will use, all of these classes will also have getter and setter methods as well as the ones outlined here.

Rigidbody:

class Rigidbody{

private:

List<Vector> vertices

Vector position

Vector velocity

Vector force

double mass

public:

constructor(vertices, position, velocity, force, mass){

this.position = position

this.velocity = velocity

this.force = force

this.mass = mass

}

method update(dt){

velocity += (this.force/this.mass)\*dt

this.position += this.velocity\*dt

}

method draw(renderer){

renderer.drawVertecies(this.position, this.vertices)

}

Method project(axis){

double min = dot(axis,vertices[0]+position)

double max = min

for (int i=1; i<shape.vertices.length; i++){

double p = dot(vertices[i]+position)

if (p < min) min = p

else if (p>max) max = p

}

return {min, max}

}

}

ImGUI uses pointers to interact with variables, so this class will also contain getters for pointers to some of the attributes so that the user can edit them using the Object Information Panel.

Circle:

class Circle inherits Rigidbody{

private:

double radius

public:

constructor(position, velocity, force, mass, radius){

Rigidbody([], position, velocity, force, mass)

this.radius = radius

}

method draw(renderer){

renderer.drawCircle(this.position, this.radius)

}

method project(axis){

point = dot(axis, position)

return [point-radius, point+radius]

}

}

The projection for a circle is slightly different than one for a normal polygon as the circle has no vertices stored, the traditional project will not work. The alternative method is to project the centre position and then the minimum point will be that minus the radius, and the maximum will be that plus the radius.

Mainloop:

This is a flowchart of the mainloop of the program, the loop executes once per frame.

Diagram

Description automatically generated

Features of the mainloop:

Update Rigidbodies – This is where the program loops through the rigidbodies and softbodies and calls their update function, this function will move the bodies. Softbodies will also change their structure in this function.

Check Collisions – This is where collisions are detected, for every detected collision, resolve collisions is called.

Resolve Collisions – This is where the program will change the properties of the two colliding objects to resolve the collision, this involves changing their velocities depending on the simulation conditions and the momentum of the two objects.

Update ImGUI – The program changes any ImGUI properties that need to be changed, this includes changing the menu, updating any values shown etc.

Render Simulation – The simulation is rendered onto the window here, this will involve drawing all of the bodies as well as any borders.