

Physics for Game Developers

(10 Week Lesson Plan)

Lesson 1: Basic Concepts

Textbook: Chapter One (pgs. 1 – 24)
Appendices A and C

Goals:

We begin the course by introducing the student to the concept of real-time physics in game engines. We will start by discussing why physics is such an important topic in the game industry and how it can make a difference in your next state of the art game. Then we will talk about the scope of the overall course and begin discussing the five fundamental steps to designing real-time physics simulations for games. We will start with a decision about what we will model and move on to look at how we can then begin developing that model for our simulation. In the process we will get an overview of many of the concepts we will cover in detail in this course, including Newton's Laws, mass properties, collision handling, numerical integration, and system tuning. We will then introduce the fundamental mathematics we will need in order to develop our physics simulations. We will start with a discussion of coordinate systems and units of measurement. Then we will talk about important vector operations, including the cross and dot products, and also introduce quaternions and some of their key operations. We will develop reusable classes for these two types for later use in our simulations.

Key Topics:

- 5 Fundamental Steps for Creating Real-Time Simulations
- Deciding what to Model
 - Example: Shooting Simulation
- Developing the Model Overview
- Collision Detection and Response Overview
- Impulse Method
- Integrating the Equations of Motion
- Tuning
 - Example: Fluid Simulation
- Units of Measure and Coordinate Systems
 - Earth fixed and Body fixed coordinates
- Vector Operations
 - Dot/Cross Products
- Quaternion Operations

Projects: NONE

Exams: NONE

Recommended Study Time (hours): 10 – 12

Lesson 2: Modeling Part I

Textbook: Chapter One (pgs. 1 – 24)

Goals:

In this lesson, we will introduce the concepts of particles and rigid bodies as the lead in to our discussion of developing our model. Our initial discussions in modelling will focus on mass properties, mass, center of mass and moment of inertia. We will look at how to calculate the various mass properties and see how things work in a 2D example using a hovercraft. Then we will examine the use of 3D primitives as bounding objects for our rigid bodies. From there we will look at the inertia tensor, symmetry, and transfer of axes for products of inertia. Next we will introduce our multi-element rigid body data structure and look at an example of how to calculate important mass properties like the total mass, center of gravity, and the inertia tensor. We will conclude the lesson with an introduction to Newton's equations of motion.

Key Topics:

- Particles vs. Rigid Bodies
- Physics Based Modelling
- Mass Properties
 - Mass
 - Center of Mass
 - Moment of Inertia
- 3D Primitives
 - Circular Cylinders and Cylindrical Shells
 - Rectangular Cylinders
 - Spheres and Spherical Shells
- The Inertia Tensor
 - Products of Inertia and Symmetry
 - Transfer of Axes
- Rigid Body Data Structure
 - Element Data Structure
- Airplane Mass Properties Calculation Example
 - Total Mass
 - Center of Gravity
 - Relative vs. Combined Center of Gravity
- Newton's Laws of Motion
 - Newton's 2nd Law of Motion

Projects: NONE

Exams/Quizzes: NONE

Recommended Study Time (hours): 10 - 12

Lesson 3: Classical Kinematics

Textbook: Chapter Two (pgs. 25 – 56)
Chapter Six (pgs. 101 – 120) * optional

Goals:

With our core concepts now in place, students are introduced to the subject of kinematics. In this lesson we will focus on displacement, velocity, and acceleration and talk about how these concepts are related to one another. We'll look at the differences between particles and rigid bodies in terms of kinematics and go over some important kinematics relations used when developing real-time simulations. We will begin with a quick introduction to derivatives and integrals, which are two calculus concepts that will play important roles in our development of a physics engine. Then we will discuss linear displacement, velocity and acceleration in detail and look at the kinematic equations of motion. Some useful formulas will be introduced for problems involving constant acceleration. We will then talk a bit about simple projectiles and develop a data model for point masses. This will ultimately lead us into our first look at rigid body rotation. We will conclude the lesson with an exploration of angular displacement (rotational velocity and acceleration).

Key Topics:

- Derivatives and Integrals
- Linear Displacement
 - Linear Velocity
 - Linear Acceleration
- Kinematic Equations of Motion
- Simple Projectiles
 - Particle FX
 - Particle Explosion
 - Data Structures
- Rigid Body Rotation
 - Angular Velocity
 - Relative Velocity
 - Angular Acceleration
 - Relative Acceleration

Projects: Cannon1, Cannon2
Particle Explosion

Exams/Quizzes: NONE

Recommended Study Time (hours): 10 - 12

Lesson 4: Force

Textbook: Chapter Three (pgs. 57 – 68)
Chapter Seven (pgs. 121 – 145) *optional
Chapter Eight (pgs. 146 – 162) *optional

Goals:

In this lesson students will develop a solid understanding of force from both theoretical and practical points of view. This is an important first step before introducing kinetics in the next lesson. The first topics we will cover will be force, pressure, and torque and look at how these concepts are related and why they are relevant to game physics. We will also discuss the various types of forces that are commonly used in game physics engines and talk about some practical formulas for calculating these forces. Some of these ideas will include friction, fluid dynamic drag, fluid dynamic lift, buoyancy, and springs and dampers.

Key Topics:

- Force
- Pressure
- Torque
- Field Forces
- Friction
 - Coefficients of Friction for Common Surfaces
- Fluid Dynamic Drag and Lift
 - Common Coefficient of Lift
- Magnus Lift
- Buoyancy
- Springs and Dampers
- Other Applied Forces

Projects: NONE

Exams/Quizzes: NONE

Recommended Study Time (hours): 6 - 8

Lesson 5: Kinetics

Textbook: Chapter Four (pgs. 69 – 86)
Chapter Nine (pgs. 163 – 167) *optional

Goals:

Rigid body kinetics is the heart of game physics engines. Kinetics is the study of the motion of objects – position, velocity and acceleration – with regard to the forces acting on those objects that initiate or affect the objects' motion. In order to fully appreciate the subject of kinetics, students must have a firm grasp of the subject of kinematics and a good understanding of the concepts of forces and moments. The first several lessons of this course were aimed at providing such an understanding, so at this point, we do not have to introduce any new theory. So far in this course we have discussed Newton's laws of motion, the equations of motion for both particles and rigid bodies, the subject of kinematics, and forces & torques. These are all the ingredients we need in order to study kinetics. What we will do in this lesson is review key elements of the material covered so far and outline a strategy for solving kinetics problems. Moreover, we will reinforce this strategy by considering a few examples.

Key Topics:

- Newton's Laws of Motion
 - Equations of Motion
- Kinematics Review
 - Forces and Torque
 - Relative Velocity and Acceleration
- Steps to Solve Kinetics Problems
- Hovercraft Simulation Example
 - Hovercraft Properties
 - Forces
 - Data Structures
 - Initialization
 - The Simulation Loop
 - Stepping the Simulation
 - Calculating Loads

Projects: Cannon2, Cannon3

Exams/Quizzes: NONE

Recommended Study Time (hours): 8 - 10

Lesson 6: Numerical Integration

Textbook: Chapter Eleven (pgs. 172 – 183)

Goals:

In the last lesson we took a look at a simple hovercraft simulation that was based on the principals of kinematics and kinetics. There were, however, some parts of the example code that were glossed over since we had not yet covered the theory behind the code. Specifically, we are referring to the part of the code that performs numerical integration on the equations of motion in order to step the simulation through time. In this lesson, we will focus on numerical integration and take another look at the hovercraft example code that deals with integrating the equations of motion. The first thing we'll do in this lesson is walk through the concept of numerical integration from a casual perspective. Then we will formalize the techniques in terms of several well known methods – the basic Euler method, an improved Euler method, and the Runge-Kutta method. We will discuss advantages and disadvantages with these methods and look at code samples illustrating implementation of these methods in the context of a real-time simulation.

Key Topics:

- Numerical Integration
- Acceleration to Velocity
- Velocity to Displacement
- Euler's Method
 - Graphical Interpretation
 - Instability
- Improved Euler's Method
- Runge-Kutta Method
- Other Methods
- Accuracy versus Stability

Projects: NONE

Exams/Quizzes: NONE

Recommended Study Time (hours): 10 – 12

Lesson 7: Rotation in 3D

Textbook: Chapter Fourteen (pgs. 223 – 229)
Chapter Fifteen (pgs. 230 – 248)

Goals:

In this lesson we are going to look at integrating the equations of motion in 3D in the context of a 3D flight simulation. Before we get to that though we have to address how we are going to handle rotation in three dimensional space. We will take a look at how to use quaternions to represent rotation and orientation in 3D. Then, we will revisit the equations of motion in 3D, particularly the angular equation of motion, and look at an example of how to numerically integrate these equations of motion. After we cover rotation in 3D, we will have almost everything we need to develop some fairly sophisticated simulations.

Key Topics:

- Rotation in 3D versus 2D
- Rotation Matrices
 - Orientation and Matrices
- Quaternions
 - Quaternions and Rotation
 - Quaternions and Angular Velocity
 - Quaternions and Vectors
- Euler Angles
- Angular Equation of Motion
- Flight Simulation Example
- Stepping the Simulation
- Calculating the Loads on the Airplane

Projects: 3D Flight Simulation

Exams/Quizzes: NONE

Recommended Study Time (hours): 6 - 8

Lesson 8: Collision Response I

Textbook: Chapter Thirteen (pgs. 205 – 222)

Goals:

Now that we can make things move and fly around in our simulations we need to figure out what happens when our objects bump into each other. For this, we will consider collision response. Over this lesson and the next, we will explore collision response in physics-based simulations in both 2D and 3D. The first thing we will address in this lesson is the difference between collision detection and collision response – these are two distinct problems. We will then briefly review what the collision detection algorithms need to do in order to work with our collision response algorithms. Regarding collision response, we will focus primarily on the impulse method and we will look at how to apply this method for both linear and angular collision response in 2D.

Key Topics:

- Collision Detection
 - Collision Data
- Collision Response
- Impulse Method
- Impact
 - Line of Action
 - Coefficient of Restitution
- Linear Collision Response
- Linear Impulse
- Angular Collision Response
- Angular Impulse
- Stepping the Simulation
- Animation

Projects: 3D Hovercraft
3D Collision

Exams/Quizzes: NONE

Recommended Study Time (hours): 6 - 8

Lesson 9: Collision Response II

Textbook: Chapter Thirteen (pgs. 205 – 222)
Chapter Sixteen (pgs. 249 – 270)

Goals:

In the last lesson we looked at linear and angular collision response in 2D. Further, we examined some code samples that implemented collision detection and response in the context of a simple hovercraft demo. In this lesson we'll pick up where we left off last lesson and continue our discussions of collision response. We will build on what we learned by extending collision response to 3D. Further, we will take a look at how to handle friction at the point of impact and examine why we would want to include a consideration of friction in our collision response code. We will also discuss resting contact versus collision. To wrap things up we will see how all of these elements are implemented in the context of a billiards example.

Key Topics:

- Impulse Including Linear and Angular Effects
- Friction
 - Impulse and Friction
- Contact
- Collision Data
- Billiards Example
 - With and without friction
- Ball-Ball Collision
- Ball-Ground Collision
- Ball-Ground Contact
- Resolving Collisions
- Resolving Contacts

Projects: Billiards

Exams/Quizzes: NONE

Recommended Study Time (hours): 7 - 9

Lesson 10: Case Studies

Textbook: Chapter Thirteen (pgs. 205 – 222)
Chapter Seventeen (pgs. 271 – 284)

Goals:

In this lesson we will go back and take another look at the billiards example as a case study since it includes all of the elements that we have discussed in this course and will let us see how everything fits together. We are essentially going to walk through the five steps involved in developing real-time game simulations that were introduced in Lesson 1. As we go through each of these steps, we will discuss why we did things the way we did in this simulation and examine specific code samples that actually implement these steps. Then we will highlight the important elements comprising another simulation. Instead of a rigid body simulation, we will look at how the same principles we have been discussing throughout this course can be applied to model a non-rigid object. The key elements in this lesson will be using particles and spring-damper systems to yield a very simple model to simulate cloth. We will wrap things up with a discussion of some recommended further areas of study for students wishing to continue their game physics education.

Key Topics:

- What to Model?
 - Balls and Table
- Mass Properties Code
 - Inertia Tensor
- Collision Detection and Response
 - Contact and Rolling Resistance
 - Aerodynamic Drag
 - Linear and Angular Drag
- Equations of Motion
- Stepping the Simulation
- The Main Loop
- Tuning
- The Cloth Model
 - Springs and Dampers
 - Spring-Damper Particle System
- Drag, Wind Forces
- Tension and Shear Spring

Projects: Billiards
Cloth Simulation

Exams/Quizzes: NONE

Recommended Study Time (hours): 10 - 12

Final Examination

The final examination in this course will consist of 100 multiple-choice and true/false questions pulled from the presentations and textbook chapters. Students are encouraged to use the lecture presentation slides as a means for reviewing the key material prior to the examination. The exam should take no more than two hours to complete. It is worth 100% of student final grade.