

Classical Mechanics I

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These notes were prepared between November 2025 and (tentitive) (**Last update: January 4, 2026**).

If you find any mistakes or typos, please report them to caccacpenguin@gmail.com. I would really appreciate it.

I often use informal language to make the ideas easier to grasp. My goal is to make the material feel approachable, while still respecting the rigor of the subject.

I hope you will find these notes helpful :D!

References

These books serve as our main references.

- Herbert Goldstein, Classical Mechanics, 2nd Ed. Addison-Wesley, 1980.
- L. D. Landau, E. M. Lifshitz, Mechanics
- Torsten Fließbach. Mechanik: Lehrbuch zur Theoretischen Physik I, 7. Auflage, 2015.

Other great texts:

- H. Stephani, G. Kluge, Klassische Mechanik, Spektrum Verlag
- F. Scheck, Theoretische Physik 1: Mechanik, Springer-Verlag
- V. I. Arnorld, Mathematical Methods of Classical Mechanics, 2nd. Ed., Springer, 1989

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1 Introduction

Physics is one of the most fascinating fields of science, its purpose is to predict the future and reconstruct the past of every particle in the Universe. It has tremendous applications especially to engineering but to chemistry, biophysics, neuroscience, cognitive science and much more. It is probably not wrong to say that physics is the most fundamental of all natural sciences.

It's lowkey deadass that our universe can be understood by using mathematics rather than say poetry. However, it is important to distinguish the mathematical models from the real universe.

Many people treat mathematics as the reality. We see the phrase “the universe is written in the language of mathematics” being thrown around a lot. However, the fact is: our theories are just mathematical models of the reality. There is a difference between these two statements. The difference is that our physical interpretation of the mathematical concepts come from the experimental observations, but it is not reflected in the formalism.

Mathematical physics is just family of mathematical models, we apply those models to certain situations when the conditions are met, and to properly understand when and where our models apply we need to understand their foundations and study the axiom system and the model formally.

This change of philosophical perspective will help us understand why our models don't work at certain situations and directly target those problems rather than just trying new objects and hoping it would work.

However, reality is not a mathematical structure either because there are some things that our models alone cannot explain without something outside the system, our axioms themselves come from empirical observations and to make sense of where the models apply you need physical interpretation which is not part of the formalism.

There's no shame about admitting that we don't understand nature we just use models. We don't really understand what the “physical aspect” of our models are, what are forces? What really are quantum particles? These philosophical questions are hard to answer even though our models work spectacularly and we make predictions and experimentally confirm them up to several decimal places.

Our formal system mostly focuses on the syntax, the semantics is not there. For example, quantum mechanics tells us that an electron is: A representation of the Poincaré group, state in a Hilbert space, with eigenvalue of mass, spin, parity. But this is just the mathematical object. The formal system says nothing about the physical electron. You need semantics for physical interpretation, ontology for what exists physically and epistemology for how we know it (the experimental part).

And the biggest issue of Physics, as it exists today, is: syntactically hand-wavy, semantically incomplete, ontologically ambiguous, and absent epistemology.

You might be worried, thinking, “*If physical theories are just mathematics then how are we to talk about atoms and elementary particles if we can't precisely model them?*”

Indeed, it does seem like we can't talk about atoms and elementary particles, if you take physical interpretation completely out of the picture, then there would be no point in calling this physics. We study physics because we want to understand nature.

But this is not true, we can talk about these phenomena if we consider the semantics of our theories. The point of the above discussion was to strictly separate the mathematical formalism from the physical interpretation and not to throw away the physical nature of the theories altogether.

Physicists don't really care about language and precision, they just want to make predictions; but to truly understand physical theories we must be clear about what we are talking about and what we are not.

Our approach will be to study the mathematical models rigorously and understand where they can be applied to solve practical problems. The focus is on conceptual understanding, formal rigour and mathematical precision. But we won't neglect practical applications either, and we'll solve plenty of problems as well.

In the first volume, we'll focus on analytical dynamics of Hamiltonian and Lagrangian systems, symmetries and the Hamilton-Jacobi Theory. Special Relativity will not be covered here, it will be covered in a combined notes with General Relativity in *Theory of Relativity*.

These notes are not self-contained, you need basic knowledge: Analysis I and II, Linear Algebra I and II. Apart from them, only elementary understanding of Newtonian Mechanics is expected.

2 Newtonian Mechanics

In the first chapter we'll review Galileo and Newton's formalism and the three axioms along with some basic concepts of mechanics, but we'll do it more rigorously than elementary courses. These concepts will be used in every subsequent course. Understanding them is crucial to understanding almost all of physics.

2.1 Galilean Space-time

First we examine some experimental facts which are the basis for our axiom system and mechanics.

Definition 2.1. **Space** is a three-dimensional, oriented Euclidean space \mathbb{E} .

Definition 2.2. **Time** is described by a one-dimensional, oriented Euclidean space, represented by the continuum \mathbb{R} of the real numbers, using the order \leq on \mathbb{R} as orientation and the usual distances between numbers.

Definition 2.3. Galilean Spacetime is a four-dimensional affine space $\mathcal{G} = (\tilde{\mathcal{P}}, \mathcal{V}, +)$, consisting of a set $\tilde{\mathcal{P}} = \mathbb{R} \times \mathcal{P}$ with $\mathcal{P} = \mathbb{R}^3$ of point-like spacetime events, a vector space $\mathcal{V} = \mathbb{R} \times \mathbb{E}$ and an addition operation, together with a linear form $\Delta: \mathcal{V} \rightarrow \mathbb{R}$, whose kernel $\mathbb{E}_0 := \ker \Delta := \{v \in \mathcal{V} | \Delta(v) = 0\}$ is endowed with a Euclidean inner product, making \mathbb{E}_0 a three-dimensional Euclidean space.

Newtonian mechanics is the study of particles and systems of particles in a 3-dimensional Euclidean space.

2.2 Galilean Group

Newtonian mechanics is all about particles but what exactly *are* “particles”? We are told that: particles are small objects that can be treated as point masses. However this definition is oversimplified and not precise. In reality, there is no such thing as a particle, no object has “zero dimensions” and treating them as such is only an application of the object but not the true definition of the object itself.

Below I provide a formal definition of a particle:

Definition 2.4. A **particle** is a point in an affine space associated with a scalar, $m \in \mathbb{R}^+$, called mass of the particle.

Remark 2.5. In the framework of Newtonian mechanics, particles have *only* two properties, its position and its mass. Asking about any other property such as charge, spin, shape, size or colour of the particle is meaningless. These properties are not defined in this framework and hence cannot be discussed.

Technically, we're being unclear about what we mean by *mass* here. For now, we assume that mass is understood intuitively as a measure of the amount of matter in the particle, for now we treat it as a coupling constant, a positive real number. We will make these concepts more precise later on.

You may ask, “*Okay, but what does a particle physically represent?*”

A particle is a model of small objects whose dimensions are negligible compared to the length scales involved in the problem.

We can *apply* this model to physical objects only when the conditions are appropriate. For example, when studying the motion of planets around the sun, we can treat the planets and the sun as particles because their sizes are negligible compared to the distances between them. When talking about planets as particles we can only talk about its position and mass at a certain instance and not about its magnetic field strength, the amount of water on the planet or the colour of the planet.

However, when studying the motion of a real object it is not clear how to apply this model. For example, when studying the motion of a car, we cannot meaningfully assign position to a spinning, flying car and treat it as a particle, do we assign the position at the trunk or at the steering wheels? However, we'll see in future sections how almost all objects can be modelled as a particle if we consider the motion of its center of mass.

You might feel, "*This abstract idea of a particle is a bit difficult to grasp.*" Of course it can be, to make it easier, think of a particle not as a physical object but pair of two numbers (a, b) where a represents the position of the particle and b represents its mass. Formally we don't represent particles in this way, it's just a simple analogy to help you separate the intuition from the abstract concept.

You might also wonder, "*Why do we even need this abstract definition of a particle? Why can't we just do physics in the intuitive way like we used to?*"

The reason for why we're being so strict about separating the formalism and the interpretation is because our intuition can carry us only so far. When we study more advanced topics, such as quantum mechanics or general relativity, concepts get highly abstract and our intuition often fails us. Developing a habit of thinking precisely and clearly will be helpful in the long run.

3 Lagrangian Mechanics

Definition 3.1. A **configuration space** is a smooth manifold Q of dimension n , where each point $q \in Q$ represents a unique configuration of the system.

4 Hamiltonian Mechanics