Determinism is Critical to Physical Theories

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1 Abstract

This essay delves into the multifaceted concept of determinism within the domain of physics, scrutinizing prevalent definitions and classifications. Navigating through the nuances of deterministic behavior, we distinguish it from colloquial interpretations of "non-deterministic." By examining determinism through the lenses of natural laws, weak determinism, and strong determinism, we unravel the intricate relationship between predictability and the underlying mathematical structures of the universe. Classical mechanics serves as an exemplar of deterministic principles, while statistical mechanics introduces complexities that challenge simplistic classifications. The interplay between ignorance and non-determinism emerges as a pivotal consideration, urging a nuanced understanding of deterministic frameworks amidst intricate systems. In essence, this exploration seeks to reconcile the richness of deterministic behavior with the complexities inherent in the natural world.

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2 Introduction

The fabric of reality, as woven by the laws of physics, is intricately entwined with the notion of determinism. Our journey commences with a poignant historical anecdote involving Einstein's response to a young inquirer, setting the stage for the profound implications of determinism in scientific inquiry. The foundational definition posits that the world adheres to determinism if, given a specified state at a certain time, subsequent developments are inexorably fixed by natural law. However, this seemingly straightforward definition prompts a deeper exploration into the nature of determinacy.

A pivotal perspective arises—defining a world's determinacy by its inherent properties, irrespective of temporal or spatial considerations. The elucidation of this viewpoint necessitates a robust defense, unveiling key tenets. The ability to define states within a system becomes paramount, intertwined with the prerequisite of unchanging laws and a fundamental axiom that a world devoid of laws cannot embrace determinism.

As the essay unfolds, causal determinism converges with the universality of physical laws, culminating in a tripartite classification of determinism: weak, strong, and physical laws determinacy. Each classification unravels layers of intricacy, delving into the essence of deterministic behavior within the framework of natural laws and mathematical structures.

Our journey extends into classical physics, exemplified by the deterministic bastion of classical mechanics. Newtonian laws lay the groundwork, and subsequent developments by Lagrange and Hamilton cement deterministic predictability within this realm. Yet, as we traverse into statistical mechanics and thermodynamics, a subtle interplay emerges. The emergence of seemingly non-deterministic properties poses a challenge, prompting a discerning exploration of the relationship between deterministic principles and the complexities inherent in these domains.

The discourse takes a crucial turn as we confront the dichotomy between ignorance and non-determinism. The label "non-deterministic" often masks our epistemic limitations, portraying intricate phenomena as a departure from deterministic principles. An astute examination reveals that complexity and determinism need not be adversaries; instead, complexity enriches deterministic frameworks, demanding a sophisticated understanding of the intricate systems that govern our physical reality.

In this exploration of determinism, our endeavor is not merely to dissect definitions but to reconcile the precision of deterministic behavior with the inherent complexities of the natural world. The subsequent sections navigate through intricacies, unraveling layers of deterministic principles and mathematical structures, ultimately fostering a profound appreciation for the order woven into the fabric of the cosmos.

3 What is Determinism?

In 1936 Einstein replied to a young girl at sixth grade, who sent him a letter:

> "*Scientific research is based on the idea that everything that takes place, is determined by laws of nature.*"

The idea is roughly simple and probably seems trivial to the people of scientific inquiry. Any event in the world is necessitated by antecedents and conditions, together with the laws of nature. Therefore we would define the term determinism as:

> ***Definition*** 1 –The world is governed by determinism if and only if, given a specified way things are at a time t, the way things go thereafter is fixed as a matter of natural law.

Such a definition is a good one to start with. But I have concentrated my opinion around another definition, which I would argue is better than the one we've just seen.

> ***Definition*** 2 –A world has a property called determinacy if and only if given a system with a specified state and the laws of nature, one candefine future and past states of such a system, regardless of time and position of the system in the world (as long as they don't matter).

Surely I have to defend such a definition. But some keynotes are important to notice in this definition:

- First off, we have to have the ability todefine a state, of a system in such a world. This means that the structure of the world and also the physical theories developed for such a world should in principle be capable of uniquely distinguishing between two different states and two different systems.
- Secondly, there assumed to be laws governing the world to exhibit determinacy; to my knowledge, no lawless system is even able to have deterministic behavior, since anything can be the right path for the state to evolve on. Thus the predictability, which is a property that would come out of the box, in a world of deterministic behavior, is gone. Therefore I would suggest that we keep it like an axiom. That a world without laws cannot be deterministic.
- At the end, most importantly, the laws should not change. If we want the world to have deterministic properties; this could mean that the same processes for the same systems should have the same final results, regardless of the absolute time and place taking place. (Note that if spatial and time dependencies are, in fact, there as properties for our system then what it means that we have to expand the term **system** to include for such properties).

Such a definition, in addition to causal determinism, has the universality of physical laws as a byproduct of its definition. So then wedefine three types of determinism for our discussions to have more clarity.

3.1 Weak, Strong, and Physical Laws Determinacy

Since our main objective is todefine determinacy of physical theories and the natural world and not merely the philosophical embodiment of determinism; wedefine three types of determinism that would simplify the matter:

1. **Deterministic Behavior of Natural Laws:** At first, the most general case is that, to have a deterministic world.
   (a) There has to be natural laws
   (b) These laws should be deterministic in the sense that given our state and law one can determine a set of evolutions that the system had and will undergo.
2. **Weak Determinism:** The world is said to be weakly deterministic if and only if any state and a set of laws correspond to one state in the past and only one in the future.
3. **Strong Determinism:** The Structure of the world is strongly deterministic if and only if it is corresponding to a mathematical structure.

3.1.1 Determinism of Natural Laws (DNL)

DNL, is the property of the world, which has laws of nature that do not change. This property is completely necessary to be able to have any physical theories. There's a difference between this kind of determinism and the other two, this one states that the processes of nature happen over a law, where the law itself is always determined. This is the fact that knowing the laws of nature —looking at them as a state of physical laws— they will be predictable (perhaps they won't even change) after a passage of time or change of spatial properties.

3.1.2 Weak Determinism (WD)

The reason to address two types of determinism is to be found in later notes. But for now, WD, states that one way to achieve a well-known deterministic feature under a world with natural laws is to have a one-to-one correspondence from each possible past state to only one state in the present (one for each), and then also for the future.

3.1.3 Strong Determinism (SD)

SD is my suggestion to have a foundational determinism (or to be able to conclude the absence of). It recognizes that determinism, other than WD, can be thought of being able to deduce an outcome or an equation in an axiomatic physical theory. Such deterministic behavior doesn't neglect complex, chaotic, or even random (if proven that a process would be possible but not deducible from a set of axioms) as non-deterministic; rather as a consequence of mathematical structure that is the world.

3.2 Classical Physics and Determinism

- **Classical Mechanics:** CM starts with the assumption that the particles obey a law, such a law explains the movement (acceleration) of the particles given the forces exerted on them.

  1. Every body perseveres in its state of rest, or of uniform motion in a right line unless it is compelled to change that state by forces impressed thereon.

     > "Projectiles preserve in their motions, so far as they are not retarded by the resistance of the air or impelled downwards by the force of gravity. A top, whose parts by their cohesion are perpetually drawn define from rectilinear motions, does not cease its rotation, otherwise that as it is retarded by air. The greater bodies of the planets and comets, meeting with less resistance in more free spaces, preserve their motions both progressive and circular for a much longer time."

  2. The alteration of motion is ever proportional to the motive force impressed; and is made in the direction of the right line in which that force is impressed.

     > "If any force generates a motion, a double force will generate double the motion, a triple force triple the motion, whether that the force be impressed altogether and at once, or gradually and successively. And this motion (being always directed the same way with the generating force), if the body moved before, is added to or subtracted from the former motion, according as they directly conspire with or are directly contrary to each other; or obliquely joined, when they are oblique, so as to produce a new motion compounded from the determination of both."

  3. To every action, there is always opposed an equal reaction: or the mutual actions of two bodies upon each other are always equal and directed in contrary parts.

     > "Whatever draws presses another is as much drawn or pressed by that other. If you press a stone with your finger, the finger is also pressed by the stone. If a horse draws a stone tied to a rope, the horse (if I may so say) will be equally drawn back towards the stone: for the distended rope, by the same endeavor to relax or unbend itself, will draw the horse as much towards the stone, as it does the stone towards the horse, and will obstruct the progress of the one as much as it advances that of the other."

  Through such laws, Newton describes a deterministic behavior of the weak kind. The laws of motion in classical mechanics are weakly deterministic as well as strongly —anything that is weakly deterministic would also be strongly deterministic but not vice versa—. Later development such as Lagrange and Hamilton mechanics are falling into the same type, they predict that any motion is according to the principle of least action.

- **Statistical Mechanics, Thermodynamics:** The kinetic theory of gases, thermodynamics and later statistical mechanics, follow the same principles in classical mechanics though they are able to exhibit some potential pseudo-non-deterministic properties. Apart from the obvious case for statistical mechanics where it seems that the emergent properties of pressure, volume, temperature, etc., are tied to the ignorance of observers and experimentalists, or the impotence of the theoretical physicist in calculating everything from everywhere. But nevertheless it is assumed that the adiabatic behaviors are completely deterministic, as the final state of the system is also predictable.

4 Ignorance vs non-Determinism

Many domains within physics often grapple with phenomena they might label as "non-deterministic behavior." The definitions presented in this essay aim to elucidate the nuances, challenging the reader to distinguish between what is commonly termed "non-deterministic" and the precise meaning derived from the provided definitions.

According to the definition outlined in the initial section, processes labeled as non-deterministic must inherently defy natural laws. However, such a scenario is rarely encountered in scientific inquiry. In the hypothetical situation where a process is introduced that seemingly disobeys any known laws of nature, the scientific community, grounded in the belief in a lawful universe, would approach it with curiosity and rigor. Scientists would meticulously observe the process, endeavor to formulate new models that partially describe it, and ultimately strive to derive a more encompassing law that accounts for both the pre-existing and novel processes.

In the majority of cases, the term "non-deterministic" serves as a placeholder for processes characterized by intricacy and/or chaos. It is crucial to recognize that using "non-deterministic" in this context is often a semantic convenience rather than a declaration of a fundamental absence of natural laws. This distinction becomes a potential pitfall for those seeking to comprehend determinism. The challenge lies in avoiding the assumption that complexity or chaos inherently implies a departure from deterministic principles. Instead, these situations may reflect the inherent intricacies and sensitivities within deterministic systems, requiring more sophisticated models and methodologies for accurate description and prediction. Thus, embracing the complexity within deterministic frameworks is essential for a more nuanced understanding of the intricacies inherent in the natural world.

- **Deterministic Behavior of Natural Laws:** The deterministic behavior of natural laws presupposes the existence of these laws governing the world's processes. When one uses the term "non-deterministic" in the context of complex or chaotic phenomena, it doesn't dismiss the foundational requirement that natural laws must exist. The complexity may arise not from a lack of laws but from the intricate interplay of these laws in systems that exhibit sensitivity to initial conditions. In essence, the term serves as a convenient label for intricate dynamics within deterministic frameworks rather than indicating the absence of governing laws.

- **Weak Determinism:** Weak determinism posits that for a world to be weakly deterministic, any given state and set of laws correspond to one state in the past and only one in the future. The colloquial usage of "non-deterministic" does not challenge this definition. In situations labeled as non-deterministic, the emphasis is often on the intricacies of predicting future states rather than a contradiction to the idea that a specific past state corresponds to a unique future state. The apparent non-deterministic nature might be a reflection of the sensitivity to initial conditions, not a denial of weak determinism.

- **Strong Determinism:** Strong determinism asserts that the world is strongly deterministic if and only if it corresponds to a mathematical structure. The informal use of "non-deterministic" to describe complex phenomena does not contest this definition. Even in systems labeled as non-deterministic, there exists an underlying mathematical structure governing their behavior. The complexity arises from the richness of this mathematical structure, not from a departure from determinism. In this sense, the term "non-deterministic" serves as a descriptor for the intricate mathematical relationships within strongly deterministic systems.

5 Conclusion

In unraveling the intricacies of determinism within the realms of physics, our exploration has ventured through various definitions and classifications. The dichotomy between what is often labeled as "non-deterministic" and the precision inherent in our definitions has been a central theme. As we conclude, it's imperative to distill the essence of our journey.

Determinism, as framed by the deterministic behavior of natural laws, hinges on the foundational concept that the processes of nature unfold over laws that remain constant. The predictability and orderliness of these laws underscore the deterministic nature of our physical world. This deterministic behavior, however, does not preclude complexity; rather, it thrives on the intricate interplay of laws, manifesting as sensitivity to initial conditions.

The distinction between weak and strong determinism further refines our understanding. Weak determinism posits a one-to-one correspondence between past and future states, emphasizing predictability within the bounds of natural laws. Strong determinism takes a leap into the mathematical fabric of the universe, asserting that the world is deterministic if and only if it aligns with a specific mathematical structure. Even in systems labeled as "non-deterministic" in colloquial terms, the richness of the underlying mathematical structure persists, showcasing the complexity within deterministic frameworks.

Classical mechanics, with its laws of motion, epitomizes deterministic behavior. The principles articulated by Newton, Lagrange, and Hamilton set the stage for a deterministic universe, where predictability arises from the governing laws. As we traverse into statistical mechanics and thermodynamics, potential pseudo-non-deterministic properties emerge. Yet, these apparent deviations are rooted in the complexities of large ensembles and emergent properties, not a fundamental departure from determinism.

The dichotomy between ignorance and non-determinism surfaces prominently. Often, phenomena labeled as "non-deterministic" merely reflect our limitations in understanding and modeling intricate systems. Embracing this complexity within deterministic frameworks becomes paramount for a nuanced comprehension of the natural world.

In essence, our exploration underscores that complexity and determinism are not mutually exclusive. Instead, complexity enriches deterministic systems, unveiling layers of intricacy that demand more sophisticated models and methodologies. As we navigate the vast landscape of physics, acknowledging the interplay between deterministic principles and the rich tapestry of mathematical structures fosters a more profound appreciation for the order inherent in the natural world.