Heuristic Physical Engine is All You Need

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Abstract

The intuitive ability to reason about physical dynamics is an indispensable and unique aspect of human intelligence. Over the past decades, researchers have proposed a series of methods to model human's intuitive sense of physics, among which mental simulation approaches stand out. Mental simulation approaches win favor due to their accurate predictions in many scenarios and generalization ability to unseen tasks. However, they are criticized because they fail to predict common human misconceptions, and the simulation processes are time-consuming. This essay proposes a novel framework termed **Heuristic Probabilistic Physical Engine (HPPE)**, which combines traditional heuristic approaches and probabilistic physical engines, aiming at combining their strengths and compensating for the deficiencies. Just as the biological assumption that humans are shaped by nature and nurture, we argue that humans predict physical dynamics by heuristics and simulations.

1 From heuristic approaches to physical simulation

Intuitive physics refers to the ability to "understand the physical environment and interact with objects and substances that undergo dynamic state changes, making at least approximate predictions about how observed events will unfold." How the objects rest on and support each other, whether stable or not, and how they will evolve when a force is applied to them—-we must have an intuitive grasp of this knowledge to understand and interact with the environment. It is identified that a set of cortical regions in the brain are engaged when people watch and predict the unfolding of physical events, and these regions overlap with those involved in action planning and tool use, signifying an intimate relationship between understanding physics and preparing an appropriate action [3].

Researchers have debated the mechanism for humans' intuitive sense of physics from philosophers to psychologists. At the center of the debate is whether the human mind utilizes an engine to simulate physical dynamics and predict future states or simply relies on heuristics accumulated with experiences. Heuristic approaches are based on pre-defined rules, fast and accurate in some scenarios. However, they are defective in generalization, i.e., they can hardly make accurate predictions in noisy, unseen environments, and as the rules accumulate, the search space becomes too massive to bear.

In contrast, theories of the probabilistic physical engine (PPE) [1] become popular because the PPE only needs to encode basic Newtonian mechanics and can model humans' perceptual errors by adding noise to objects' attributes, demonstrating a generalization ability across domains and tasks. However, those approaches are questioned as the simulation process is time-consuming and complicated, inconsistent with the high efficiency of human minds. There are several features of PPE that are incompatible with human cognition [6]:

1. **Object tracking**. The simulation engine keeps track of every object in the environment, representing their positions and updating them according to physical rules. The amount of objects often exceeds what humans can identify, remember, and track. Human limits vary by domains and tasks but are often identified as around seven items, plus or minus two [7].

2. **Temporal consistency**. The simulation engine predicts objects' states step by step, with time order. Every time click, all attributes of all objects are calculated and updated, which is usually not the case in humans. Humans can inversely predict previous states according to the final state or infer bi-directionally, not limited by chronological order. Besides, humans can focus on certain attributes and states essential for prediction, saving time and energy.
3. **Probability coherence**. People are not always probabilistically coherent and, in certain cases, will estimate conjunctions to be more likely than one of their components, termed conjunction fallacy. People sometimes make conjunction fallacy errors, but the conjunction rule will not be systematically violated in the simulator.
4. **Systematic errors**. Physical simulation approaches attribute human mistakes to perceptual errors and sample objects' attributes from a Gaussian distribution. However, human perceptions might be biased, not fitting a Gaussian distribution. For example, when presented with acoustic stimuli, the auditory system segments continuous input into discrete event representation, causing illusions in which perceived duration is distorted [2] [5]. Moreover, human minds may not encode all Newtonian mechanics like the engine, or some rules can be false, causing systematic errors during physical prediction. For instance, some people might think force is the reason for maintaining the motion of objects.
5. **Developing nature**. Human minds are developing with the accumulation of time and experiences. Humans are endowed with a few separate core knowledge systems, where new, flexible skills and belief systems build on [9]. However, initially, the physics engine is encoded with all basic Newtonian mechanisms and will not update its rules with new cases, which is inconsistent with the developing nature of human cognition.

Despite the plausible performance of the probabilistic physical engines, their deficiencies cannot be ignored. In the Sec. 2, we demonstrate that introducing proper heuristics into the simulator can partly solve these drawbacks. We term the novel simulator a Heuristic Probabilistic Physical Engine (HPPE).

2 Heuristic probabilistic physical engine

The heuristic probabilistic physical engine (HPPE for short) combines a heuristic module and a physical engine module, combining their strengths. The heuristic module makes fast, rough estimations, while the physical engine is responsible for slow, accurate simulation. Just as humans possess two systems for fast and slow thinking [4], HPPE can decide which module to utilize depending on whether the scenario is familiar and whether there is enough time [8].

2.1 Physical engine module

Compared with conventional probabilistic physical engines (PPEs), the physical engine module has limitations on calculation. It can only track N items at most, be it individual objects or object groups. There are also boundaries on time limits and memory, as humans can only memorize a small set of object states at a time and predict several steps in the future. Our physical engine module is energy-saving and more consistent with human cognition.

2.2 Heuristic module

The heuristic module has several functions.

Firstly, it can make quick, rough estimations depending on heuristic rules. Take the scale problem as an example. Humans tend to think the scale will tilt to the side with more objects or the side where objects are placed farther to the center. When the two conditions are met simultaneously, humans intuitively think the scale will tilt to a certain side without calculating the dynamics step by step.

Secondly, the heuristic module can provide heuristics for the physical engine, guiding the simulation process. Which part is most likely to be unstable, which objects can be regarded as a group, at which point the objects might collide, whether it is possible to simulate objects one by one or inversely predict their states, which attributes are most important during simulation—-these are the questions human will think when reasoning physical dynamics. If the heuristic module can answer these

questions and provide the information to the physical engine, the simulation efficiency will greatly improve.

Thirdly, the heuristic module has an inductive reasoning module responsible for generating new heuristic rules from experiences. Each heuristic rule is assigned a confidence value, showing how confident they can be used in reasoning. For instance, the heuristic module may learn from observations that "force is the reasoning for changing the motion of objects." As more and more evidence accumulates in support of the heuristic, its confidence gradually increases, and the confidence of its opposite heuristic, "force is the reasoning for maintaining the motion of objects," gradually decreases to zero. The generation and disappearance of heuristic rules align with the developing nature of human cognition.

2.3 Violation of expectation

The expectation of HPPE refers to its prediction of physical dynamics. When observed physical dynamics violate its expectations, the heuristic module evaluates the heuristic rules' confidence. It sends rules with lower confidence to the physical engine for hypothesis testing. The physical engine module then verifies the hypothesis by making simulations with or without certain heuristics or even creating new scenarios and tasks to conduct testing. This process is similar to what children do when their expectations are violated. After simulation, the physical engine module sends information back to the heuristic module to update the confidence of certain rules.

3 Outlook

Future research directions lies in:

- How are heuristics represented and used to guide the probabilistic physical engine?
- How are heuristics generated and induced from experiences, and how is the confidence assigned?
- How does the physical engine conduct inverse prediction and bi-directional simulation?
- Can we utilize visual illusions to investigate the structure of the physical engine?

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