Automating the foundations of physics, starting from the experiments

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Disclaimers

- The talk has no connection to the conference.
- I’m not competent to give the talk.
  - I don’t know enough philosophy of science.
  - I don’t know nearly enough physics.

However,

- I’ve been thinking about this for 35 years.
- I don’t have a better venue
- I don’t know of anyone else who has thought about it in these terms.
- I hope you folks will be interested.

Starting point

There exist online verified, complete symbolic proofs of deep mathematical theorems, starting from foundational theories:

- Prime Number Theorem (Avigad, Harrison)
- Feit-Thompson Theorem (Gonthier)
- Kepler Conjecture (Hales)
- Most of the thms in undergraduate math

(There is nothing comparable for applications or word problems, though.)

Mathematical ideal

A mathematician who publishes a proof of a theorem could, if required, write down the whole proof from first principles.

Generally the model in math education and textbooks.

Informal poll on this rule in practice in math

Pro: "Possible or not, this should be a goal."

"Vladimir Voevodsky very much strives toward this ideal."

Whitehead: "I would no more use someone's theorem without reading the proof than I would use his wallet without permission."

Con: "I couldn't have a career in pure math if I held myself to the standard you describe."

Can this be done for Physics?

Going from experimental descriptions and results to theories.

Example: Conservation of energy in chemical reactions

- Some number of separate experiments.
- Each of the forms of energy involved (chemical, heat, phase change etc.) has to be measured.
- Each experiment is a procedure of manipulations, observations and measurements:
- Stuff is poured, mixed, heated, collected.
- The equipment itself (scales, thermometers, …) has to be validated.

Similar thoughts

Hilbert's 6th problem: *Mathematical Treatment of the Axioms of Physics.*

The investigations on the foundations of geometry suggest the problem: *To treat in the same manner, by means of axioms, those physical sciences in which already today mathematics plays an important part; in the first rank are the theory of probabilities and mechanics.*

Similar thoughts

- "The Master Algorithm is the germ of every theory: all we need to add to it to obtain theory X is the minimum data necessary to induce it. In the case of physics, this would be the results of perhaps a few hundred key experiments."

Pedro Domingos, *The Master Algorithm*

Bayesian formulation (as straw man and framework)

Space of scientific theories Φ.

Experiments/observations E.

Outcomes D_E

$$\text{argmax}_{H\in\Phi} P(H|D_E) =$$
$$\text{argmax}_{H\in\Phi} P(D_E|H) \cdot P(H)$$

Leave aside the question of probabilities.

In what language can one express all possible theories in Φ, *and all possible experiments* E?

Is there a theory-neutral language of experiments?

Bayesian formulation

- Excludes concept learning.

  E.g. Suppose that physics contains a statement about electrons.

  That statement has a prior probability.

  Therefore, the concept of electrons must exist *ab initio.*
- However, concept formation is inherently problematic (Fodor).

Mathematical Concepts

Concepts are formally defined in terms of foundational concepts e.g. set theory.

- A rational number is an equivalence class of integer pairs.
- A group is a pair of a set and an operation that is associative, has an identity, and has an inverse.

Whether this exhausts the intuitive meaning of these concepts is debatable.

Automated concept exploration in math

AM (Lenat, 1977)

- Starting with set theory, built up concepts such as
  - Natural numbers
  - Addition
  - Multiplication
  - Prime number
  - Maximally divisible number

A *Gedanken* Meta-experiment

Sonya is a student. Tatyana is a teacher.

Tatyana is trying to teach Sonya physics.

Sonya is very bright, but skeptical; she takes as little as possible on faith.

Specifically Tatyana needs to show Sonya:

- Sufficient experimental evidence for every theoretical claim.
- Justification, theoretical or empirical, for every piece of equipment

Limits to skepticism

Sonya accepts:

- The approximate validity of human perceptions.
- The approximate validity of commonsense physics.
- “Raw” data at the level published in reputable venues
- The integrity of the scientific infrastructure.

Tatyana

- Chooses and presents the experiments.
- Explains the concepts.
- Teaches the standard terminology.
- Presents the theory that the experiments support.
- May not cherry pick results. E.g. show data points that lie perfectly on the theoretical curve.

With Tatyana’s help, Sonya’s task is much easier than that of the scientific community facing the world.

She can focus on the right issues.

- The general relation of the tides to the moon may be worth including.
- The specifics of timing and height of the tides is probably too complicated to include.
- There is no point trying to relate the movement of the planets to the fall of empires.

Analogously in math, Tatyana

- Singles out the theories that are worth studying.
- Defines the concepts
- Presents the proofs.

What is “all of physics”?

- Let’s say “All the physics that a physics major is expected to know.”
- Lower bound: The foundational theories: quantum theory; fundamental fields and forces; elementary particles; general relativity.

Why the foundations don't suffice: Super-elementary phenomena

- Atoms
- Light
- Cosmology
- Thermodynamics = Stat. mech. (or is that foundational?)

More questionable cases:

- Sound is longitudinal pressure waves.
- Lightening is electricity. Ferromagnetism.
- Chemical bond is determined by interaction of outer electrons.

Why the foundations don't suffice: Grounding

- The equation of gravity is just a differential equation.
- You have to understand its manifestation in experiments and observations:
  - Objects on spring scales
  - Falling objects
  - Solar system
  - Tides
  - Stars
  - Cosmology

Why the foundations don't suffice: Grounding

- The equation of gravity is just a differential equation.

$$m\frac{d^3 x_i}{dt^2} = \sum G m_j \frac{x_j - x_i}{|x_j - x_i|^3}$$

- You have to understand its manifestation in experiments and observations:
  - Objects on spring scales
  - Falling objects
  - Solar system
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  - Cosmology

Why the foundations don't suffice Universality

Rubner's demonstration of conservation of energy in a dog is an important experiment for *physics;* it shows that the constraints of physics apply to animals.

Informal argumentation

- Essentially eliminable in mathematics
- Not eliminated in physics. In practice "arguments from first principles" include:
  - Ignore issues judged to be irrelevant
  - Ignore quantities judged to be negligible
  - Argument by analogy
  - "Physical intuition" (perhaps analogy)

Can we restrict Tatyana to presenting the experiments?

- Hard to make sure that Sonya stays on the right track. Once she deviates, that may snowball.
- A coherent description of an experiment is in terms of concepts that have been developed. Hard or impossible to describe an experiment in a theory-neutral language.
- Even if Sonya develops an equivalent theory, it may be hard to relate her terminology to ours.

Can we automate Sonya?

What is the inductive bias? Preference for:

- Simplicity?
- Symmetry / invariance?
- Mechanistic explanations?
- Mathematics? Specifically, real analysis?
- Spatially/temporally local theories? Specifically differential equations?

Two particular cases

- Cosmological distances
- Periodic table of the elements

Cosmic Distance Ladder

- Astronomical unit
- Stars with measurable parallax
- Measurements within galaxy
- Measurement of distance to other galaxies.

Depend on some regularity within a class of objects. E.g. the relation between brightness and period in Cepheid stars.

Draws on other physics (e.g. spectrographic theory)

Example: Periodic Table

- Law: If the elements are ordered by increasing atomic weight, the chemical properties are periodic.
- Important for structure of electron orbitals and verifying that chemical properties depend on orbitals.
- Experiments:
  - Determining the elements, their atomic weights, and their chemical properties
  - Determining that there aren't a lot of other elements.

My own research

- Developing a formal language in which physical behavior can be described at the commonsense (mesoscopic) level.
- Support for qualitative reasoning.
- First-order language with naïve set theory and real arithmetic.
- Solids, liquids, gasses.
- Containers.

Some sample inferences

- If a container remains closed, then matter cannot go from inside to outside.
- Liquid can be carried carefully without spilling in an open container.
- If you put rocks into a pail of water, the level of the water will rise.
- The reaction $2H_2 + O_2 \rightarrow 2H_2O$ consumes twice as many moles of H_2 as of O_2.

Speculations: This might ..

- Be a useful framework to think about the relation of theory to empirical data in physics.
- Allow us to extend the technology of math verification to physics.
- Be a path toward rich, automated scientific reasoning.

Conclusion

- Carrying out this project for college physics would be orders of magnitude larger than formally verifying college math.
- It might require more advanced physics as justification for equipment.
- We are far from a formal or computational theory of inducing scientific theories from experimental data.