The Role of Metaphor in Scientific Thought and Physics Education

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Outline

- Analogies in quantum mechanics and cognitive-historical analysis
- Metaphors and cognitive linguistics
- Heat & Thermodynamics
- A very short note on ontology
- A model
- Some predictions, implications and examples
Schrödinger
[“Quantisation and Proper Values II” Annalen der Physik (4) 79 (1926)]

Hamilton’s analogy between classical mechanics and geometrical optics (descriptive)

Hamilton-Jacobi Eqn → Eikonal Equation

\[ W - \text{Hamilton’s characteristic function} \rightarrow L - \text{optical path length or phase of the wave} \]

Lines of constant \( W \) in configuration space → Lines of constant \( L \)

Particle trajectories perpendicular to const. \( W \) lines → “Rays” of light.
Schrödinger

A different perspective

- Schrödinger supposed that the analogy was “exact” in the following sense:

**Diagram:**

- Geometrical optics
  - Analogy
  - In the limit of small apertures replace with
  - Wave theory of light
- Classical mechanics
  - Analogy?
  - Breaks down in similar manner to geometrical optics.
  - Wave theory of matter
Schrödinger

Total phase \[ \propto \text{Total phase} \]

Proportional to \[ \propto \text{Proportional to} \]

Plug into \[ \text{Plug into} \]

Reduces in small \[ \lambda \] limit to: \[ \text{Reduces in small } \lambda \text{ limit to:} \]

Plug into \[ \text{Plug into} \]

Reduces in small \[ h \] limit to: \[ \text{Reduces in small } h \text{ limit to:} \]
Schrödinger

- Use of analogical modeling
- Use of knowledge which is familiar to him.
- Small extensions of existing ideas.
- Over-extension of the model. (What are the major limitations of this picture?)
- Case for an historical approach to understanding student difficulties?
Cognitive-historical Approach
(Nancy Nersessian)

“Continuum Hypothesis”

Physicists make extensive use of analogical reasoning.

Physics students often generate models of physical phenomena very similar to models seen in the historical development of concepts in physics.

Can we use the inventors of quantum mechanics as a loose analogical model to understand what our students are thinking?
A model of student reasoning

Inventors of quantum mechanics

Base knowledge
Confusion
Argument
Mental modeling
Language use
Analogy

Base

Students learning quantum mechanics

Misconceptions
Preconceptions
Confusion
Students
Primitive knowledge
Language use
Explanations

Target
A model of student reasoning


- Not a “literal similarity”
- Map objects so as to preserve the relational structure (Just like an isomorphism)
- Systematicity Principle: (Map based on the deepest possible relations)
Schrödinger

A different perspective

- Schrödinger supposed that the analogy was “exact” in the following sense:

  Geometrical optics \(\overset{\text{analogy}}{\leftarrow}\) Classical mechanics

  In the limit of small apertures replace with

  Wave theory of light \(\overset{\text{Analogy?}}{\leftrightarrow}\) Wave theory of matter

  Breaks down in similar manner to geometrical optics.
A model of student reasoning

Positive Analogy

- Students struggling with classical notions. Generation of conceptual change.
- Student models very similar to original models and pictures of the “experts”.

Negative Analogy

- Experts reason productively from their base knowledge, student metacognitive & epistemic processes are weak.
- Expert background is strong, student background is weak.

Neutral Analogy

- What’s going on with the language?
A linguistic digression

Connections between thought, language and cognition:
- Vygotsky
- Sapir and Whorf - Sapir-Whorf hypothesis
- Lakoff and Johnson - Language and cognition are both metaphorically structured.

How does language facilitate and/or constrain our thought processes?

What does language tell us about how we think?
Cognitive Linguistics

“We dissect nature along the lines laid down by our native languages … We are thus introduced to a new principle of relativity, which holds that all observers are not led by the same physical evidence to the same picture of the universe, unless their linguistic backgrounds are similar, or can in some way be calibrated.”

-B.L. Whorf

- Hopi conception of “time” - events are counted in ordinals.

- Compare with a “Western” conception of time.

- Some interaction between how we talk and how we perceive and make sense of the world.
Cognitive Linguistics

“Let's strike a blow for clear thinking by ridding the English language of the word *heat* as a noun.”

- Physics is replete with examples of physical quantities spoken of as nouns
- E.g.: Force, heat, work, energy, time, etc…
- It has been argued that these “quantities” may be better viewed as *processes*.
- What does that tell us about how we think?
Cognitive Linguistics

“Our ordinary conceptual system, in terms of which we both think and act, is fundamentally metaphorical in nature…”
[G. Lakoff and M. Johnson, *Metaphors We Live By*

Language is largely metaphorically structured.  
Our conceptual system is largely metaphorically structured.

- What role does metaphor play in physics?
- What can a metaphorical analysis of the language of physics tell us about how physicists think?
- What can a metaphorical analysis tell us about what our students are thinking?
What is a Metaphor?

The Interaction View (Max Black)

- Metaphor: A mechanism by which systems of ideas interact.
- Metaphor acts as a filter through which something is viewed.
- Metaphor is an organiser of ideas and concepts
- Metaphor creates similarity

Communal wolf stereotype
Ontological Metaphors

Roughly speaking: Metaphors which endow concepts/ideas/systems with some type of existence.

- **Substances/entities**
  - “He broke down” (*The mind is a machine*)
  - “Heat flows…” (*Heat is a fluid*)

- **Personification/human desires/mental states**
  - “Inflation is eating up our profits”
  - “The system wants to remain in its ground state”

- **Spatial orientations and containers**
  - “Land is in sight” (*Visual field as container*)
  - “She is at the peak of her career”, “His status fell” (example of *more is up, less is down*)
Metaphorical Grounding

Ontological metaphors are an example of metaphorical grounding.

Abstract ideas in terms of “concrete” experiences
  - “Experiential basis” for many metaphors
  - Eg: seeing is touching: “He could not take his eyes off her”

Directly emergent concepts
  - Concept of “causation” Agent → Patient → Perceptible change

Emergent concepts are metaphorically elaborated (often in terms of ontological metaphors)
  - The object comes out of the substance
    - “I made a paper plane out of computer paper”
  - The substance goes into the object
    - “I formed the clay into a statue”
  - Causation is emergence of an object/event from a state/container
    - “He shot the mayor out of desperation”

Ontological metaphors are an example of metaphorical grounding.
Emergent concepts are understood in terms of a “core prototype” [See E. Rosch]

- Core prototype of causation is necessarily metaphorically elaborated and therefore always reducible.
- Core prototype, although having structural similarities across cultures, will also have an experiential component which is metaphorically elaborated and therefore culturally situated.
“… we say that heat energy [their italics] - to which we give the symbol $Q$ - flows from the system to the environment.”

“… we choose $Q$ to be positive when heat flows into a system and negative when it flows out of a system. [their italics]”

“Energy can also be transferred between a system and its environment by means of work… [their italics]”

“Both heat and work represent energy-in-transit between a system and its environment.”

“A heat pump is a device that - acting as a refrigerator - can heat a house by drawing heat from the outside, doing some work, and discharging heat inside the house.”
Heat & Thermodynamics

Douglas C. Giancoli, Physics for scientists & engineers, third edition

“…scientists came to interpret heat not as a substance, and not even as a form of energy. Rather, heat refers to a transfer of energy: when heat flows from a hot object to a cooler one, it is energy that is being transferred from the hot to the cold object.”

“We would expect that the internal energy of a system would be increased if work were done on the system, or if heat were added to it.”

James S. Walker, Physics

“Heat is the energy transferred between objects because of a temperature difference.”

“…we will use common expressions such as ‘heat flow’ and ‘heat transfer’ to refer to the energy transfer associated with heat.”
Heat & Thermodynamics

Heat is a fluid/substance, system/gas is a container, engine is a pump/agent:
- “Heat flows/is transferred into/out of system”
- “Heat capacity”, “Heat reservoir”, “Heat pump”

Energy is a fluid/substance, system/gas is a container, heat/work is substance and agent/process:
- “Energy flows/is transferred into/out of system by heat/work”
Heat & Thermodynamics

Heat/Energy

(as fluid) (as substance)
“flows” "is transferred” “is put/taken”
“is moved” “goes from” “is added to”

gas/system/substance/cycle/engine as container

environment as container
environment as reservoir (Fluid container)

“expelled/rejected/exhausted/leaving/pass through”

“absorbed from/drawn in from/enters/pass through”

engine as mover/“pump”

by process: heat/work as agent

Tentative diagram of the linguistic apparatus that we use to talk about thermodynamic processes.
Heat: History and student misconceptions

The Historical development of heat and thermodynamics matches the metaphors.

Student misconceptions about heat can be explained by considering overextensions of this metaphorical system.
Ontology


- Three basic classes/categories of ontology
  - Matter, processes, states
- Conceptual change involves movement of concept from one ontological category to another.
- E.g.: Evidence suggests many physics students see heat as a substance. Physics experts understand heat as a process.
- No explanation as to why students classify processes in the matter category.
Model

- Physicists need to assert “is” rather than “like”:
  - Is this common to human cognition?
  - Assertions of fact hide the vague/partial nature of the metaphor itself.
- Metaphor is fundamental in interpreting one system of “figuring stuff out”.
  - [Sutton, C. “Figuring out scientific understanding.” J. Res. Sci. Teach. 30 (10), 1215-1227 (1993).]
Model

Metaphors encode figurative thinking
- The figurative origins of the ideas are lost (Sutton)
- These metaphors are not “dead” - they are metaphors physicists live by.

Metaphors represent primitive encodings (diSessa 1993) of ideas/concepts in physics
- Limitations of picture is communally well understood.
- Problem: Metaphors themselves do not convey those limitations
Model: Metaphor and analogy

- Established physical theory: System of metaphors
  - Encoded in terms of
  - Interact via:
    - Metaphorical superposition
    - Analogy
- New, unfamiliar system
  - Becomes
- New physical theory
Model: Grounding

1. Metaphors grounded in experience common to the physics community
   - Light is a particle/light is a wave

2. Metaphors grounded in prior theories.
   - Heat is a fluid comes from the caloric theory of heat

3. Metaphors grounded in analogies which are useful pictures but not full-blown physical theories
   - Potential energy graphs are water wells

4. Metaphors which mirror the ontological grounding observed in language:
   - Processes elaborated in terms of substances
   - Causation elaborated in terms of movement of substances into and out of containers
   - Spatial metaphors for time, momentum etc…
Eg1: A Metaphorical System in Quantum Mechanics

“Potential energy graphs are water wells”

Entails: “Energy is a spatial dimension”, “energy is a fluid”

Language: “Potential well”, “energy level”

Leads to productive modes of thought:

Notion of Confinement
Narrow the walls & water (energy level) rises up

Emission is Escape
(A new metaphorical system)

Tunneling Metaphor
Leaking Metaphor

Thicker walls imply more time

Entails:

- Energy is a spatial dimension
- Energy is a fluid

Language:

- Potential well
- Energy level

Thicker walls imply more time
Model: Grounding

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Newtonian Mechanics

Common phrases, system 1:
- “The force of object A on object B”
- “Object A exerts a force on object B”
- “Tension in the rope”, “What is the object’s weight?”

Common phrases, system 2:
- “A force of 50N acts on the object”
- “Centripetal force”, “Normal force”, “Friction”
Newtonian Mechanics

Metaphorical system 1:

(1) Objects are animate and are the agents of change; (2) force is a substance which is contained within these objects; (3) Change (acceleration) happens through a process of contact with or touch on the “patient”.

Metaphorical system 2:

(1) “Sources” of forces/interactions, external to the system under consideration, are ignored. (2) The force itself is metaphorically elaborated, both as an object and as an autonomous, animate agent. (3) Change happens through a process of contact with or touch on the “patient”.
Newtonian Mechanics

- Note similarity to emergent concept of causation and its metaphorical elaboration
- Grounding of process in terms of touch/contact
- Personification of either the object (system 1) or the force itself (system 2).
Newtonian Mechanics

Passive objects don’t exert forces
Force is a property of the object
Larger objects have more force
Students invent extra forces
Students struggle to see the gravitational force as legitimate force.
Confusion between inertial and non-inertial reference frames
Model:
Predictions/Implications

Metaphorical systems tend to be misleading.

- They suggest figurative ideas as fact.
- They seem to introduce ontological conflicts (e.g., interpreting processes in terms of substances)

Is there a correlation between students’ ability to distinguish meanings of terms and their ability to solve related physics problems?

Can we make a useful analogy between mastering the nuances of a second language and learning physics?

Can we teach physics students to stop and ask: “What does that phrase actually mean?” And approach answering that question with language comprehension skills as well as knowledge of physics.
Model: Predictions/Implications

Students have to go through the same ontological “shifts” that expert physicists do in order to “understand” something.

Can predict students’ difficulties, misconceptions by looking at:

1. Types of difficulties/ideas which physicists had when developing the model
2. The language used by physicists when talking about the model.

Is there a linguistic component to the contextual dependence of students’ knowledge?
Born

[“Quantum Mechanics of Scattering” ZS. f. Phys. 38, 803 (1926)]
Translation at www.physics.rutgers.edu/~dbrookes/research/Born/Born.html

- Generative analogy almost trivial
- Particle travels within the confines of a guiding wave
- Needs a second analogy to make useful physical predictions
Born

- Second analogy between a quantum system and a statistical ensemble

<table>
<thead>
<tr>
<th>Ensemble</th>
<th>Quantum system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of atoms</td>
<td>Number of atoms</td>
</tr>
<tr>
<td>in state $n$</td>
<td></td>
</tr>
</tbody>
</table>

Born almost never uses the word “probability” (wahrscheinlichkeit), but prefers to use the term “frequency of occurrence” (häufigkeit).

- Develops scattering theory as a prediction to test both analogies
Born

• **Predictions**
  – Predicts interference patterns from scattering principles:
    “The dependence of the yield on direction is determined by the function $A$. This apparently corresponds to diffraction.”

• **Testing**
  – “A proof of our formalism from the data will follow later.” [see Ramsauer, Davisson & Kunsman, Dymond and others.]

• **Awareness of Limitations**
  – “…the proposed theory is not in accordance with the consequences of the causal determinism of single events.”
  – Born seems aware that his generative analogy has limitations
Two Competing Metaphorical Systems

“Electron is a wave”

• Productive modes
  - Diffraction of electrons.
  - Measurement as “disturbance” - wave pattern is destroyed. (Hodges)
  - Fourier analysis analogies for wave functions and Heisenberg uncertainty principle.

• Breaks down...
  - What is oscillating?
  - Thinking about individual particles.

“Electron is a particle”

• Productive modes
  - Electron scattering
  - Understanding what we observe at low “intensities”.
  - Basic QM problems, eg: particle in a box etc…

• Breaks down...
  - Thinking about any wave-like phenomena.
Two New Metaphorical Systems

“Electron is a wave”

Schrödinger Metaphor
“Particle is a smeared paste, contained in the wave”

Metaphorical Exchange

“Electron is a particle”

Bohmian Metaphor
“Wave function/state Contains the particle”
**Expert use (Productive modes)**

Prof B: *(Question: What does a photon look like?)*
“…you can make a packet of photons of different wavelengths to make some sort of localised pulse, so photons were not going to have to be spread out in plane waves or anything like that…”

Prof B: (On probabilistic interpretation of the wave function)
“…particles…follow the intensity of the wave.”

Prof V: (Explaining the Heisenberg uncertainty principle)
“…you can have a very well defined spatial frequency which is to say a very well defined momentum, but now the particle is very spread out.”
Question: An electron is prepared in the ground state of an infinite square well of width L. The walls are suddenly shifted to a width of 2L. Calculate the probability of finding the electron in the ground state of the new system.

Context: Two students work on this problem for half an hour, calculate the “overlap” integral and find an answer for the probability. Then one student tries to make physical sense of his answer…