Workshop Session 3

WHAT DO THE MODERN SCIENCES OF THE MIND TELL US ABOUT HOW WE COME TO UNDERSTAND SCIENTIFIC CONCEPTS?

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We outline "big ideas" from the fields of **science education**, **developmental psychology** and **cognitive science** that we find are particularly relevant to characterizing how scientific concepts are understood and how this understanding develops.

Science education

- *Alternative conceptions research* - A lot of research since the 1970's has been describing what learners' lay understanding of scientific concepts is before they begin formal instruction: some alternative conceptions hinder learning (and persist despite instruction) and some are seen as useful.
- *Two dominant perspectives*:

Concepts as embedded in theories *(e.g. McCloskey, 1983)*	*Knowledge-in-pieces* *(e.g. diSessa, 1993)*
- Lay and scientific concepts are characterized in terms of **networks** of concepts - Difference between lay and scientific understanding characterized in terms of **representation** of, and **relationship** between, key concepts in a domain (e.g. heat and temperature) - Process of change as transformation from one **"coherent" theory to another** - Accounts of change emphasize **discontinuity**	- Lay conceptions as consisting of **disorganized** knowledge **fragments** - Fragments are expected to be generalizations over **sensorimotor experiences** (e.g. *force-as-mover*) - Process of change as a process of **reorganizing existing fragments** - Accounts of change emphasize **continuity** at level of knowledge elements but change in **conditions of application**
We believe that **elements of both perspectives are needed** for an accurate account of concept learning in science.	

- Research over the last 4-5 decades has documented various important influences on the process of conceptual change and mechanisms of change: ontological classification (see below), metacognition and epistemological beliefs; modeling and analogical reasoning; social interaction (see Amin, Smith, & Wiser, 2014, for review)

Developmental psychology:

- *Conceptual development builds on two foundations:*
    - Core cognition: Abstract (possibly innate) concepts guide concept learning in the early years in core domains such as inanimate objects, animate agents, number and space; continuity in a human being's conceptual life can be attributed to these core domains. (Carey, 2009)
    - Image-schemas: These are generalizations over sensorimotor experience and are seen as a bridge between *per*ception and *con*ception. Examples of image-schemas include: *containment*, *possession*, *self-motion, animate motion*, *linked paths*, *movement along a path, inanimate motion and caused motion*. Conceptual categories are represented in terms of collections of image schemas in early childhood (e.g. animals versus artifacts) (Mandler, 2004).

- *Mechanisms of conceptual development have been proposed:*
    - Domain specific knowledge growth and metacognition (itself a "domain") replace domain general (stage) theories in the Piagetian tradition (Carey, 1985)
    - Conceptual enrichment around core concepts versus radical conceptual change
    - Reorganization of image-schemas
    - Appropriation of language-based construals (Tomasello, 1999)
    - Analogical structure mapping (Gentner, 1983, 2010), and a language-based mechanism of creative bootstrapping (Carey, 2009) enables the construction of novel concepts and explain discontinuities in conceptual development.

Cognitive science

- *Novice-expert shift:*

  i. "Classical" view

    - Problem solving: Experts tend to categorize problems based on abstract principles (e.g. energy conservation or Newton's second law); novices, in contrast, tend to focus on concrete surface features (e.g. problem involves inclined plane or rotational motion). (Chi, Feltovich, & Glaser, 1981)
    - Concept reclassification: Transition from novice to expert involves "ontological recategorization" (Chi, Slotta, & De Leeuw, 1994). For example, students'/novices' understanding of heat originates in their categorization of heat as a kind of **material substance** (a bit like the obsolete caloric theory of heat reflected in everyday language), while scientists/experts understand heat as a kind of **process**, energy transfer. In their refinement of the model, Chi and colleagues have come to differentiate between direct processes, such as a water flow, and emergent processes, such as diffusion, heat conduction, or electric currents, where interaction of the constituent entities have to be studied statistically at a collective level. Students tend to mistake emergent processes for direct processes. (Chi, 2005)

  ii. Alternative view (the contribution of "intuition" to expertise)

    - *The role of* ***intuition***: Whereas Chi and colleagues saw the ability to make abstractions as the key expert capability, Dreyfus, Dreyfus, and Athanasiou (1986) argued in their book, *Mind over* *machine,* that **recruitment of one's intuition is the true hallmark of expertise**. They contributed to the embodied cognition movement, in their refusal of the metaphor of the mind as a machine, which has pervaded traditional cognitive science. (Other contributions to embodied cognition include Merleau-Ponty (1945/2002); Gibson (1979); and Varela, Thompson and Rosch (1991)

- *The view of* ***mind as embodied***: This involves the claim that the mind is best seen as operating under conditions constrained by (and not abstracted away from) the physiology of our bodies, i.e. our brains and perceptual and motor systems, and in constant interaction with the surrounding environment, including symbolic and material artifacts.

- *Concepts as embodied:*

  - Barsalou (2008) argues that concepts, including abstract concepts, are grounded in our perceptions, in the form of imagistic mental simulations and what he calls perceptual symbols, and should not be modelled as abstract amodal symbols.

  - **Conceptual metaphor theory**: The inroad into embodied cognition in our research has primarily been through Lakoff and Johnson's (1980, 1999) theory of conceptual metaphor, systematic mappings from concrete domains to abstract domains, which are ubiquitous in everyday language; we have found such conceptual metaphors to be **pervasive in scientific language as well**, e.g. in textbooks on thermodynamics and problem-solving dialogues among undergraduate and graduate students.

  - In our view, **successful problem solving** involves **combining principle-based reasoning** (à la Chi), **with imagistic, intuitive reasoning** (along the lines of Dreyfus, Dreyfus & Athanasiou and Barsalou). Two illustrations from our own research (Jeppsson, Haglund, Amin, & Strömdahl, 2013) show how metaphor can be used in problem solving and suggest how "micro" narratives emerge that aid in reasoning:

    1. Two PhD students were asked to explain what drives the freezing of water in a beaker that is placed in a freezer. Based on the principle that the entropy increase in the surroundings will be greater than the entropy decrease in the beaker, one of the students said:

       "**if I take heat from this beaker with water… and move over to the room…** in principle, then… the partition function in… for the room will increase… more than what I lose in the beaker, then…"

       Here, conceptualization of heat, an abstract entity, as a tangible object that can be manipulated by an agent helps in visualizing and building a concrete understanding of the physical process. In this particular context, flexibly construing heat metaphorically as an object is productive, and should not be seen as an ontological miscategorization. This flexible, context-dependent use of metaphors adheres with a view of science learning as coming to use and coordinate a diverse range of cognitive (often image-schematic) resources, as put forward by e.g. diSessa (1993) and Hammer (2000).

    2. In another example, the PhD students' dialogue is centered on what characterizes adiabatic reversible processes, in reference to a diagram of the pressure of a system as a function of its volume.

With the statement "it's a question of that **one walks along the same line**", events in time are metaphorically construed as locations in space.

In addition, by imagining a person who walks along a line in relation to the studied scenario, there is integration between the phenomenon, a representation of the phenomenon (a graph), and the problem solver. However, this identification with the phenomenon through imagistic reasoning is constrained by the principled knowledge of reversible processes in thermodynamics. The "micro" narrative stands in for an extended chain of complex reasoning.

Broad conclusion:

- Both lay and scientific concepts are **complex knowledge systems**
- Developing an understanding of a scientific concept involves **incorporating new knowledge elements** of multiple formats (e.g. **image-schematic** and **linguistic**) and **reorganizing** the knowledge **system** as a whole.
- Both continuity and discontinuity need to be acknowledged.
  - **To see continuity** we have to identify **image-schematic knowledge** structures and **core concepts** present very early in life, possibly at birth.
  - **To see discontinuity** we have to describe the dramatic reorganizations that often need to occur as scientific expertise is acquired; these often involve the appropriation of specific forms of discourse, of which narrative is one example, and particular knowledge resources, such as a general understanding of emergent processes.

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