Semiotics of graph & model comprehension
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Semiotics of graph & model comprehension

1. Point of departure: Graph comprehension phenomema and phenomenographic studies

My interest in graphs and models began back in the early 1990-ies when I took part in a European research project focusing on differences and similarities between “graphical reasoning” and reasoning in natural language. My background at this time was a Ph.D. on the concept of “diagrammatic reasoning” in Charles S. Peirce, one of the founding fathers of semiotics. Later in the 1990-ies I was employed by the Technical University of Denmark (DTU) in educational studies, and there we had a project on the discrepancy between the ability of engineering students to pass traditional exams (basically based on recognition of certain types of problems and using their computational skills) and their deficient conceptual understanding of the models involved in exercises. At this time we were inspired by the phenomenographic research methods in educational studies, and Ference Marton (Göteborg University) was a consultant for our project.

In the DTU project I discovered a number of curious phenomena related to student’s understanding of graphs and models – in particular with students who had a “surface approach” (Marton) to learning. One of these phenomena has been described in the early literature on “misconceptions” in learning mathematics (e.g. by Claude Janvier and John Clement in the 1980-ies) as the conception of graphs-as-images. A school physics example by Janvier is the bicycle acceleration graph misconception:

This type of fundamental misconception of graphs (associating the graph directly with the depicted situation in the diagram to the right) seems to arise from a fundamental lack of graph reading abilities, and we could expect to find this in school pupils not trained in graph reading. However, I was surprised to find similar problems in the graph comprehension of engineering students across different domains (I will provide a number of examples in the talk), but here we have to assume that basic graph reading skills have been established in high school. So how can we explain these phenomena at university level?
2. A first approach from semiotics: confusion of “sign types” in “surface learning”

In the DTU project I attempted to show that Janvier was on the right track by calling it graphs-as-images. In the semiotics of Peirce images, graphs and diagrams are different types of “iconic signs” (signs based on a similarity relation between representation and its object), and it would appear that some students mentally deal with graphs “as if” they were images – possibly as a result of of “surface approaches” to learning, where they try to remember graphs by their graphical image-like characteristics (shape etc.) instead of understanding them as relational structures (the semantic aspect of graphs) and as expressions of underlying models (the pragmatic aspect of graphs). Some engineering students could – for instance – remember the shape of graphs in answers to qualitative/conceptual tests, but with a wrong orientation (cf. the phenomena of “mental rotation” described in cognitive science).

These disturbing phenomena came as a surprise to the teachers in engineering education, and the graph-as-images phenomena was only one type of problem. Another problem we found was the tendency to focus on prototypical graphs in a given domain and disregard the specific adaptation required when applying e.g. a physical law to a specific situation (requiring for instance a specific geometry, specific conditions). An example was Fourier’s law for heat conduction that all students had a familiarity with from high school physics, where it is discussed in the linear case of heat conduction through a wire (considered as 1-D). Here many students stick to the linear case even if the situation described concerned the 3-D heat conduction through a cylinder. This again was disturbing to teachers because these adaptations of “law schemata” to specific situations are very fundamental in engineering.

Left: Concept question testing the adaptation of Fourier’s law for (steady-state) heat conduction to the special case of a heated cylinder and graph sketching answers of students in chemical engineering (c is the correct answer). Right: The simple case of heat conduction in a thin metal wire (where the linear answer is correct) is typically the way students have been introduced to Fourier’s law for heat conduction.

In cognitive science and educational studies in the 1990-ies there was a widespread belief in the purely cognitive explanations for recurrent conceptual problems in science learning by students (such as described here and in phenomenographic studies). One dividing issue was the systematicity of misconceptions: are there in fact recurrent misconceptions in mathematics, physics, and chemistry motivated in a systematic way by
everyday experiences and prior knowledge, or should we instead consider student’s conceptions as inconherent and fragmented “knowledge-in-pieces” (as claimed by Andrea diSessa)?

3. Different approaches to “graph comprehension” and levels of meaning

In a more limited sense “graph comprehension” has been studied in a number of approaches and domains focusing on e.g.

- graph comprehension in cognitive processes (cognitive psychology)
- graph design ergonomics and perception (cognitive science)
- graph and text layout design and automation (artificial intelligence)
- graph types for information visualization (information science, statistics)
- graphs in model-based reasoning and “diagrammatic reasoning” (philosophy of science)
- graph prototypes and graph misconceptions (didactics of mathematics)

Without going into details with these very different approaches, I will mention a classification that appears across many of these and that concerns different levels of meaning construction (and that therefore links up with semiotics):

(a) A primary level of (syntactic) graph reading skills
(b) A secondary level of (semantic) graph comprehension (connecting data, graph variation)
(c) A tertiary level of (pragmatic) graph interpretation (model and real world contexts)

4. “Scientific literacy” issues and the materiality of representational forms in language and mathematics

A more complex approach from “cognitive semiotics” is under development. In recent years I have changed my mind about the original simple approach to “misconceptions” in science and how they can be seen expressed as graph comprehension problems.

In physics education research a “third position” has appeared arguing against the motivated misconceptions of “naïve physics” as well as the fragmented “knowledge-in-pieces”. In the approach of David T. Brookes og Eugenia Etkina studies of student’s knowledge of physics have to build a bridge between the two previous approaches by including the overlooked role of multimodal representational forms in language and mathematics that students are confronted with in the form of images, graphs, diagrams as well as the metaphors, analogies and gestures used to simplify and convey concepts. This indicates a kind of extended “literacy” issue of the disciplinary discourses of science. Students have to find ways to integrate all of these representations and experiences in their attempts to ground concepts in a coherent way, and this is the real context in which “graph comprehension” should be situated.

I will try to exemplify this third approach through an example from physical chemistry of an apparent misconception about the “activation energy barrier” in chemical reaction kinetics. This concerns the interpretation of graphs of the following form within teaching in enzyme kinetics (in biochemistry):
Left: “Reaction coordinate” diagram used to explain the action of enzymes with regard to lowering of the activation energy barrier. Right: Simplication (“didactic transposition” in the terminology of French didactic theory) used in one textbook to explain the “energy barrier”. This simplification is unfortunate in actually supporting a particular “misconception”, as I will explain in the talk...

Some papers associated with the discussion:


