The Use of Analogy in Physics Learning and Instruction

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Abstract

Analogies are used in the practice of physics as well as for learning and instruction. This paper briefly surveys the physics education research literature on analogy. The first part of the paper presents a rigorous theoretical framework describing analogy. The second part of this paper explores efforts by experimentalists to confirm these theories, and to test teaching strategies using analogies. The first key finding is that selection of an analogy can produce a measurable effect in concept learning. The second key finding is that students' prior knowledge plays a key role in learning by analogy.

Introduction

Analogies are ubiquitous in physics. They are used by working physicists, physics teachers, and students learning physics. James Clerk Maxwell explicitly stated his feeling that analogies were essential to his own work. In formulating a theory of electrical phenomena, Maxwell claimed:

> "Instead of using the analogy of heat, a fluid, the properties of which are entirely at our disposal, is assumed as the vehicle of mathematical reasoning...The mathematical ideas obtained from the fluid are then applied to various parts of electrical science." - Maxwell (1855)

On an analogy between heat conduction and electricity, Maxwell wrote that "The similarity is a similarity between relations, not a similarity between the things related." (Maxwell 1881). Over a century later, this idea is reflected in contemporary theories of analogy.

While Maxwell used analogies to generate new physical theory, physicists also use analogies to communicate ideas both to the public and to other scientists. Examples abound at the University of Colorado. Deborah Jin has used a metaphor* to describe the behavior of a fermionic condensate (Jin website). She compares pairs of fermions to pairs of dancers (Fig. 1). Nobel laureate Carl Wieman's research website compares a Bose-Einstein Condensate (dubbed "Bosenova") to a "tiny supernova" (Wieman website).

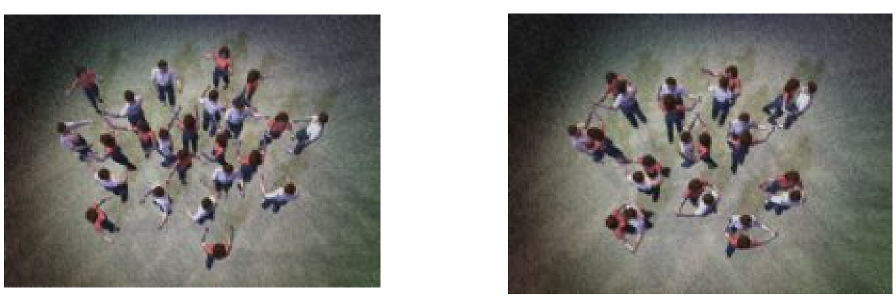

Figure 1. A metaphor for a fermionic condensate. Pairs of dancers are analogous to pairs of fermions. From Deborah Jin's website: http://jilawww.colorado.edu/~jin/

* In the literature, there is a subtle distinction between metaphors and analogies. The terms are closely related, and it will serve the purpose of this paper to use them interchangeably. For a detailed explanation, see Sutton (1978).

Some analogies may be both communicative and generative. David Bartlett has written recently on “Analogies between electricity and gravity” (Bartlett 2004), providing an historical account and application of analogy. As an historical example, consider Rutherford’s planetary model of the atom (Taylor & Zafiratos 1991). While the original utility was generative – producing a model that explained experimental results (which it accomplished better than competing analogies, such as the “plumb pudding” model of the atom) - the analogy is often used to communicate an introductory atomic model to physics students.

Thus, analogies are not only useful to working physicists, but to physics teachers as well. For instance, Coulomb’s law is often taught in introductory courses as analogous to Newton’s law of gravitation. Electric current is often likened to water flowing through a pipe. Understanding how these analogies work is a rich area of physics education research. A significant effort has gone into developing a theoretical framework for describing analogies, discussed in depth below. Simultaneously, experimentalists have asked specific research questions about the use of analogy in teaching physics concepts. For example, which analogy leads to better student learning about electric circuits – water in a pipe, or a moving crowd?

This paper will briefly survey the physics education research literature on analogy. The first part of this paper will outline contemporary theories of analogy, focusing on the domain of physics. The second part of this paper will examine the contributions by experimentalists in shaping and confirming these theories. The third part of this paper will examine analogy based strategies for teaching physics.

Models of Analogical Mapping

The Contemporary Theory of Metaphor

George Lakoff, a scholar in linguistics and cognitive science, has developed an elaborate theory of metaphor (Lakoff 1993). A subset of this theory is presented here. In Lakoff's view, the word metaphor means a *cross-domain mapping in the conceptual system*. Objects in a *base* domain are mapped to objects in a *target* domain. One of Lakoff's key ideas is that with a metaphor, a familiar situation is used to ground understanding of an unfamiliar situation. In Lakoff's terminology, Jin's metaphor would be called *The Fermionic Condensates are Dancers* metaphor, illustrated in the chart below. The base domain, dancers, is mapped to the target domain, fermionic condensates.

The Fermionic Condensates are Dancers Metaphor

Dancers (Base Domain)	**Fermionic Condensates (Target Domain)**
Dancers	Fermionic Atoms
Pairs of Dancers	Pairs of Fermions
Motion of Dancers	Condensation

The metaphor helps people understand what a fermionic condensate is. Lakoff's proposal is that the mapping is not just a novel poetic expression, but is a part of our conceptual system. In this case, the abstract idea of a fermionic condensate is *grounded* in the concrete *experience* of dancers.

Lakoff's theory of metaphor can be applied to other domains of physics. Consider the planetary model of the atom, as often taught in introductory physics courses. The mapping is shown in the table below. The base domain, the solar system, is mapped to the target domain, the atom. The dots indicate additional mappings that may be present.

The Planetary Model of the Atom

Solar System (Base Domain)	Atom (Target Domain)
Sun	Nucleus
Planets	Electrons
Sun attracts planets	Nucleus attracts electrons
Sun is more massive than planets	Nucleus is more massive than electrons

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Lakoff applies this framework to mathematics (Lakoff 2000), contributing the idea of *layering* metaphors. Briefly, metaphors can build upon other metaphors, explaining how people come to understand very abstract mathematical ideas (e.g. Euler's equation $e^{i\pi} = -1$).

Structure Mapping – A Formal Theory of Analogical Mapping

Deidre Gentner's work is often sited as foundational in the physics education literature on analogy. Gentner's view of analogy is related to Lakoff's view of metaphor, but with a formalism more familiar to mathematicians. According to Gentner's *Structure Mapping Theory*, "The analogy 'a *T* is like a *B*' defines a mapping from *B* to *T*" (Gentner 1983). *B* is called the *base* domain and serves as a knowledge source. *T* is called the *target* domain, and is the subject to be learned. Symbolically, the analogy is the mapping *M*,

$$M: b_i \rightarrow t_i$$

where the subscript *i* denotes objects (*b* and *t*) in the base and target. She illustrates this idea with an example, the planetary model of the atom. The base domain is the solar system, while the target domain is the atom. Gentner's theory allows for both *attributes* (which take one input, e.g. HOT(sun)) and *relations* (which take two inputs, e.g. ATTRACTS(sun,planet)). Fig. 2 shows a schematic representation of the mapping from the solar system to the atom. Certain attributes and relations are mapped (e.g. ATTRACTS) while others are not (e.g. HOTTER THAN). Gentner's argument is that in an analogical mapping, a large number of relations are mapped, while few

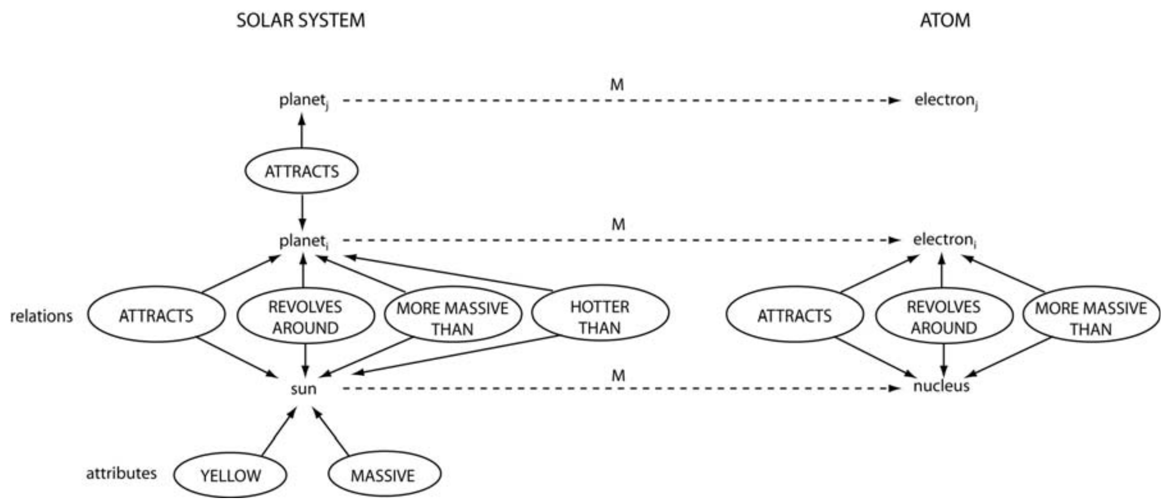

Figure 2. Structure-map for the Rutherford analogy: "The atom is like the solar system."

attributes are mapped. To differentiate analogies from other mappings, Gentner breaks domain comparisons into three categories:

1. Literal similarity – a large number of both attributes and relations are mapped (e.g. the X12 star system is like our solar system).
2. Analogy – a large number of relations, but few attributes, are mapped (e.g. the hydrogen atom is like our solar system).
3. Abstraction – the base domain is an abstract relational structure (e.g. the hydrogen atom is a *central force system*).

In summary, an analogy is a mapping of relations from objects in a base domain to objects in a target domain. Prior to the 20th century, the prevailing view was that analogy provided a convenient language, but that an exact, scientific language should exist free from metaphor and analogy (Hobbes 1651, Locke 1689). In contrast, Lakoff's views reflect the contemporary notion that analogies form a part of our conceptual system – they are part of the way we make sense of the world around us. Researchers in this camp consider analogy a mechanism of thought, emphasizing the notion of grounding in experience (e.g. Sutton 1978, Petrie & Oshlag 1993). Gentner, on the other hand, takes a more empirical approach, providing a formal theory accompanied by experimental verification. Researchers in this camp tend to skirt the issues of mechanism or experience and instead formulate testable (albeit abstract) models of analogy (e.g. Holyoak &Thagard 1997, Brophy & Schwartz 1998, Paatz 2004). These two camps do not represent a dichotomy, but rather complimentary perspectives. If these theories are correct, the consequence is that a correct understanding of the target domain requires a correct understanding of the base domain. The implication for learning physics is that students' *prior knowledge* will play a key role in the *correct* understanding of new concepts.[*]

Experiments

With a rigorous theoretical framework for analogy in hand, we can ask how the theory is borne out by experiment. Additionally, we will explore how this way of thinking about analogy is productive for learning and instruction.

Substance Based Conceptions – Analogies are Grounded in Reality

Reiner et al. (2000) conducted experiments which probed students' conceptions of physics concepts such as electricity, light, and heat. Drawing on a range of experimental results, they determined that students often used *substance based* conceptions. That is, students assigned material properties to non-material physical concepts. For example, heat flow was often conceptualized as fluid flow – heat took on the material properties of water. Based on experimental results, Reiner et al. defined a generalized knowledge of substances which includes properties such as: substances are pushable, frictional, containable, etc. These findings seem to support Lakoff's notion of grounding, and promote Gentner's mapping theory as a tool for analyzing analogical learning. Abstract ideas in physics are often thought of in terms of experiences in the real world, i.e. with material substances. Analogy provides the bridge from the material world to the abstract physics domain. In fact, expert physicists also tend to use

[*] This can be illustrated with a simple example. Supposed you wonder what bullfrog tastes like, so you ask a friend. Your friend replies that bullfrog tastes like alligator. This will not help you unless you know what alligator tastes like – your prior knowledge key for understanding the analogy.

substance based conceptions, but somehow know when these incomplete models are useful, and when they are harmful. For example, in the planetary model of the atom, planets attract each other – experts know to ignore this relational mapping to electrons, which repel. The expert's ability to invent, critique, and learn new representations has been referred to as *metarepresentational competence*[*] (diSessa 2004). Ochs et al. (1996) found that practicing scientists were adept at this skill, while diSessa, Hammer et al. (1991) also found indications of strong metarepresentational competence in sixth-graders (see also Schwartz 1993). Nonetheless, students do not always demonstrate this skill, and researchers continue to examine its development, as well as how/if it can be taught.

The Cognitive Nature of Analogy – Convenient Terminology or Generative?

One of the first questions asked by modern researchers examined the cognitive nature of analogy. According to Gentner and Gentner (1983), two hypotheses exist about the role of analogy in understanding physics concepts.

- Surface Terminology Hypothesis – analogies are merely convenient terminology. (Historical view.)
- Generative Analogy Hypothesis – analogies are used in generating inferences. (Lakoff's view.)

In order to show that analogies are generative, experimentalists had the task of showing that the inferences people make on a certain topic vary according to the analogies they use. Gentner and Gentner approached this problem using analogies for electricity.

The structure-mapping schematics of the water and moving-object analogies for electricity are shown in Fig. 3. Nodes map directly from one domain to the other (top to bottom). The node labeled α symbolizes a higher-order qualitative relation that transcends the individual domains.

[*] If we agree that representations can be considered analogies of a sort, then we could also consider *meta-analogical competence* as a valuable scientific skill.

Gentner and Gentner point out that this relation constitutes Ohm's law, but that "naïve users of the analogy may derive only simpler proportional relations such as 'More force, more flow' and 'More drag, less flow'"[*]. To the right are schematics of the intended models for an electric circuit, water system, and race track (i.e. moving object). Note that no single analogy has all of the correct properties of electric circuits, nor do these two exhaust the possible analogies for electric circuits (e.g. consider a bicycle chain).

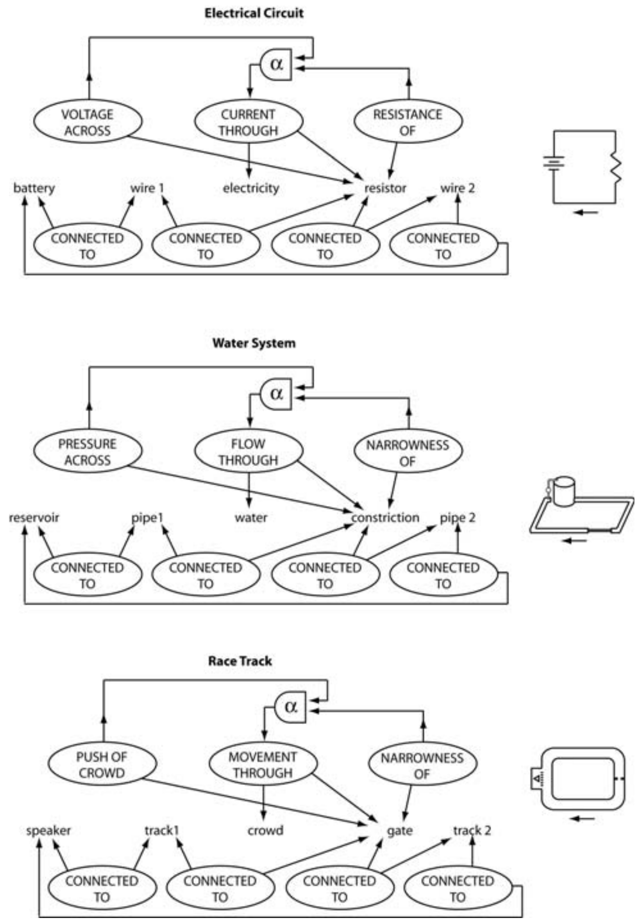

Figure 3. Structure-map for electric circuit and water system, adapted from Gentner's original paper.

In their first experiment, Gentner and Gentner gave a multiple choice exam on series and parallel electric circuits to 46 high school and college students. They then asked students to elaborate on how they thought about electricity, and from this determined whether a water analogy or moving object analogy was used[†]. Gentner and Gentner made the following predictions:

1. Students who use a water analogy should demonstrate a better understanding of batteries compared to students using a moving-crowd analogy. The reasoning is that water reservoirs are a more robust mapping to batteries than the analog in the moving-crowd model (i.e. speakers).

2. Students who use a moving-object analogy should demonstrate a better understanding of resistors compared to students using a water analogy. The reasoning is that gates provide more robust mapping to resistors than constrictions.

[*] These relations may be what diSessa (1988) terms *phenomenological primitives*.
[†] Only subjects that consistently used a water or moving-crowd analogy were included in the original results, leaving N=7 subjects using the water model and N=8 using the moving-objects model.

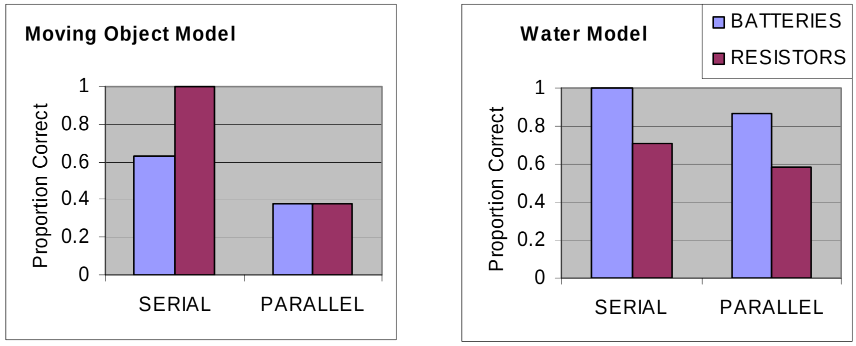

Figure 4

As shown in Fig. 4, subjects who used a water analogy performed significantly better on questions about batteries than resistors. The opposite was true for the moving-objects group. This result supported the Generative Analogy Hypothesis.

In the first experiment, students generated their own analogies. In a second experiment, students were *taught* either a water analogy or moving crowd analogy. The predictions were similar to the first experiment. Students taught the moving crowd analogy did demonstrate a better understanding of resistors, supporting the first prediction. However, the second prediction for understanding batteries was not supported. Gentner and Gentner suggested two explanations for this discrepancy:

1. Students may not have sufficient understanding of the base domain. For example, students may not understand water systems.
2. Students may not accept the model they are taught. For example, if a student is predisposed to use a moving crowd analogy, a single teaching session using a water analogy may not convince the student to use the new analogy.

Spontaneous Analogies

In their first experiment, Gentner and Gentner assumed students would generate analogies on their own. To get a more detailed view of this process, Clement (1988) explored the generation of "spontaneous" analogies by expert problem solvers (advanced graduate students and professors in technical fields). A *spontaneous* analogy is one generated without provocation.

10 experts were shown the two springs shown in Fig. 5 (with equal masses attached) and asked which spring would have a longer stretch. In explaining their thinking, 7 of the 10 experts generated significant analogies (analogies that were useful to the solution process). 31 significant analogies were generated in total. For instance, thinking of a bending diving board helped some of the problem solvers toward a solution. From observations of the experts, Clement suggested the following four processes in making productive use of a spontaneous analogy:

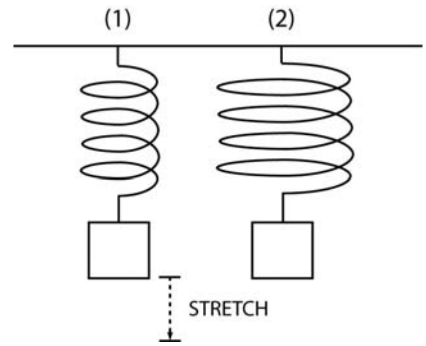

Figure 5. Springs with equal masses attached.

1. Generating the analogy.
2. Establishing confidence in the analogy relation.
3. Understanding the analogous case.
4. Applying findings.

Clement also defined three methods for generating spontaneous analogies, listed below. The number of times each method was observed, out of the 31 significant analogies, is indicated*.

1. Generation from a Formal Principle – a single equation or formal abstract principle (e.g. conservation of energy) applies in two or more different contexts. **1 Observed.**

2. Generation via a Transformation – an analogous situation *B* is created by modifying the original situation *A*. **18 Observed.**

3. Generation via an Association – the subject is "reminded" of an analogous case *B* in memory, rather than transforming *A* into *B*. **8 Observed.**

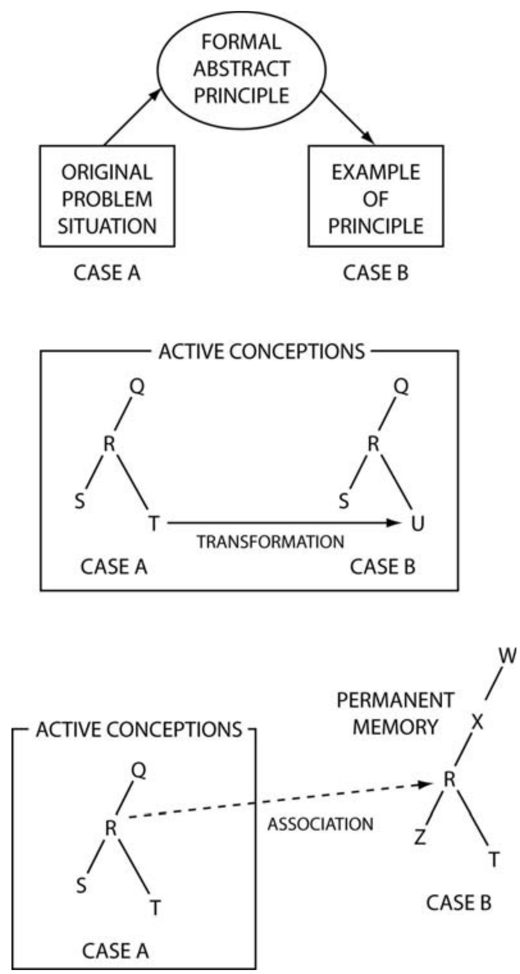

Figure 5. From top to bottom: Generation via Formal Principle, via Transformation, via Association.

* The total adds to 27 observed significant analogies. The remaining 4 were classified *Method Unclear*.

The three methods above are shown schematically in Fig. 5. This categorization of analogy represents a complimentary view to Gentner's categorization (abstraction, analogy, literal similarity).

Strategies for Teaching

Bridging Analogies and Conceptual Change

Thus far, we have examined mostly clinical studies designed to test certain hypotheses about analogy. Gentner and Gentner attempted to teach electricity concepts using analogy, but found their teaching method only partially effective. Clement's process for using analogy, while drawn from experts, could be applied to teaching students. However, studies have shown that experts and novices do not always categorize problems in the same way (Chi et al. 1981), e.g. the inclined-plane problem for the novice is a conservation-of-energy problem for the expert. If different caliber students draw on different base domains, a specific strategy may be necessary to enable students to use a particular analogy successfully. Brown and Clement explored the use of analogies in overcoming student misconceptions[*] in the target domain (Brown & Clement 1989). As suggested by Gentner and Gentner, the success of an analogy-based teaching method depends on student knowledge of the base domain (i.e. prior knowledge), and student acceptance of the analogy. Brown and Clement, claiming that students have both useful and detrimental preconceptions, attempted to build on students' useful conceptions to bring about conceptual change by using a bridging strategy defined by the following procedure:

1. A misconception is made explicit by means of a target question.
2. The instructor suggests an analogous case which will appeal to the student's intuitions.

[*] According to Redish (2003), a misconception is a particular mental model or line of reasoning that is robust, but is in contradiction to scientific theory, and found in a significant fraction (20% or more) of students.

3. If the student is not convinced of a valid analogy, the instructor attempts to establish the analogy relation. The student is asked to make an explicit comparison between the base and target.
4. If the student still does not accept the analogy, the instructor attempts to find a "bridging analogy" (or series of analogies) conceptually intermediate between the base and target.

Interviews were conducted with four students, each student having a different misconception. Using the bridging strategy, the interviews achieved noticeable conceptual change in two cases, but failed in the other two cases. Brown and Clement suggest that the differences were due to the type of analogy used. In the failed analogies, the base shared only abstract form with the target. In the successful analogies, the base and target shared some material features, instead of only abstract form. This may mean that what Gentner refers to as an *analogy* is more productive for conceptual change than an *abstraction.* Further, Brown and Clement's method revisits Lakoff's idea of layering – for a sufficiently abstract concept, a series of intermediate steps may be necessary. More formally, consider an abstract mapping A→B. For the analogy to be successful, it may be necessary to provide an intermediate domain C, resulting in the series of mappings A→C→B.

This step-wise process is a commonly applied method of teaching with analogy (e.g. Glynn 1991). Alternative methods exist, such as simultaneous comparisons of two domains (Kurtz, Mao, & Gentner 2001, Brophy & Schwartz 1998). However, these alternatives represent the cutting edge of experimental work on teaching with analogy.

Textbook Examples

The textbook is a basic tool used in most physics courses. Physics textbooks make extensive, if not always explicit, use of analogies (Curtis & Reigeluth 1984, Iding 1997). Thus, analogies form not just a theoretical and experimental domain of education, but are regularly used in the most standard physics courses. The following are examples of analogies found in a popular text (Halliday, Resnick, & Walker 1991)[*].

- Coulomb's law is like Newton's law of gravitation.
- The electric field is like a temperature field.
- Storing energy in a capacitor is like stretching a spring (or lifting a book).
- The flow of electric current is like water in a garden hose.
- An *emf* device is a charge pump.
- The magnetic field is like the electric field (they are both vector fields).
- The earth is a huge magnet.
- An inductor, capacitor, resistor circuit is like a mass, spring, viscous system.
- Particles are like sending a letter, while waves are like making a telephone call.

These analogies are commonly used in textbooks, but have not necessarily been rigorously tested with students. While the above list may appeal to physics teachers, the way students make sense of textbook analogies is not well understood[†].

Future Directions

Brown and Clement explored the spontaneous generation of analogies by experts, but few studies have examined spontaneous generation by students (but see Sandifer 2003). While the water and moving-object analogies for electricity are common, there exist other analogies (e.g. bicycle chain, marbles colliding with wheels, etc. (Summers, Kruger, & Mant 1997)) that may have added instructional value. In addition, a number of analogies have proven valuable to

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[*] This list was assembled by the author. An interesting exercise would be to label these analogies according to Clement's or Gentner's categories. Difficulties may reflect the fact that the categorization represents a continuum. It may also reflect the *situated* nature of analogies. That is, the form of the analogy depends on the past experiences of the user and present context in which the analogy is used.
[†] Consider the last analogy in the list. While the physicist may understand the particular mapping, a student may have a different interpretation – for instance, that waves travel faster than particles.

practicing physicists, such as the gravitational analogy for Coulomb's law, but have not yet been rigorously studied in terms of student learning.

There remain open questions about the dynamic nature of analogical thinking. Meta-skills, such as the ability choose a productive analogy, and experts' knowledge of which relations to map, are still poorly understood. Most studies assume a one-way mapping from the base to target. So called *simultaneous* analogies may also be considered, where two analogous situations work in unison to construct knowledge of both domains. Another exciting area of research asks how students learn abstraction. Simultaneous domain comparisons may lead students to extract abstract structure and develop conceptual knowledge. However, prior research seems to indicate that, in Gentner's terminology, the *analogy* leads to conceptual change more readily than the *abstraction*. One of the principal skills of expert physicists is to think in terms of abstractions. The author's interests lie in this area, asking how students may progress from using grounded analogies to using full blown abstractions in their thinking about physics. Previous studies have explored singular analogies (i.e. from a single base to a single target). To understand abstraction, Lakoff's idea of layering may prove useful – students may develop the skill of abstraction by building upon lower level analogical thinking skills. A pilot study by the author suggests this may be a fruitful line of future research (Podolefsky et al. 2004), but much remains to be explored in this area.

Conclusion

This paper has briefly surveyed the literature on analogy in physics learning and instruction. Early studies in this area showed that analogies were more than convenient terminology, but actually generated inferences between base and target domains. When applied to physics, this means that the analogies students generate will affect their understanding of physics concepts. On the other hand, explicitly teaching a certain analogy may not directly affect student learning – students' prior knowledge can interfere (constructively or destructively) with these teaching strategies. Effective teaching strategies seem to involve analogies that are at a level that students can understand – that is, the analogy cannot be too abstract. While analogy is a rich area of research for cognitive scientists, there remain many open questions and unexplored avenues in physics education. These efforts all contribute to the broad effort by the physics education research community to enhance instruction through a better understanding of student learning.

References

Bartlett, D. (2004). *Analogies between electricity and gravity.* Metrologia 41:S115-S124

Brophy, S. P., & Schwartz, D. L. (1998). *Interactive analogies.* In D. Edelson & E. Domeshek (Eds.), Proceedings from the 1996 International Conference on the Learning Sciences (pp. 351-356). Evanston, IL: Association for the Advancement of Computing in Education.

Brown, D., and Clement, J. (1989). *Overcoming misconceptions via analogical reasoning: Factors influencing understanding in a teaching experiment*. Instructional Science, 18:237-261.

Chi, M., Feltovich, P., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. Cognitive Science, 5(2), 121-152.

Clement, J. (1988). *Observed Methods for Generating Analogies in Scientific Problem Solving.* Cognitive Science. 12(4):563-586

Curtis, R. V., Reigeluth, C.M. (1984). *The use of analogies in written text*. Instructional Science 13:99-117

diSessa, A. A., Hammer, D., Sherin, B., & Kolpakowski, T. (1991). *Inventing graphing: Metarepresentational expertise in children.* Journal of Mathematical Behavior 10: 117-160.

diSessa, A.A. (1988) *Knowledge in Pieces.* In G. Forman & P.B. Pufall (Eds.) *Constructivism in the Computer Age*. Lawerence Erlbaum Associates. Hillsdale, New Jersey.

diSessa, A.A. (2004) *Metarepresentation: Native Competence and Targets for Instruction.* Cognition and Instructions, 22(3):293-331.

Gentner, D (1983) *Structure-mapping: A theoretical framework for analogy*. Cognitive Science, 7:155-170.

Gentner, D. & Gentner, D.R. (1983). *Flowing waters or teeming crowds: Mental models of electricity*. In Gentner, D. and Stevens, A., (eds.), *Mental Models*. Lawrence Erlbaum Press.

Glynn, S.M. (1991). *Explaining science concepts : a Teaching-With-Analogies mode*. In S.M. Glynn, R.H. Yeany and B.K. Britton (Eds.), *The Psychology of Learning Science* (pp. 219-239). Hillsdane, NJ, Erlbaum.

Hobbes, T. (1651) The Leviathan.

Holyoak K.J. & Thagard, P. (1997) *The Analogical Mind.* Am Psychol. Jan;52(1):35-44.

Iding, M.K. (1997). *How analogies foster learning from science texts.* Instructional Science. 25:233-253

Jin, Deborah. Website location: http://jilawww.colorado.edu/~jin/pictures.html

Kurtz, K.J., Mao, C., Gentner, D. (2001). *Learning by Analogical Bootstrapping.* The Journal of the Learning Sciences, 10(4):417-446

Lakoff, G (1993). *The Contemporary Theory of Metaphor*. In A. Ortony (Ed.), *Metaphor and Thought, Second Edition.* New York: Cambridge University Press.
Lakoff, G. & Nunez, R. (2000). *Where Mathematics Comes From: How the Embodied Mind Brings Mathematics into Being*. Basic Books, New York.
Locke, J. (1689) An Essay Concerning Human Understanding.
Maxwell, J.C. (1885). *Abstract of Paper 'On Faraday's Lines of Force*', in *The Scientific Papers of James Clerk Maxwell*, ed. W. D. Niven (Cambridge: Cambridge University Press, 1890; New York: Dover, 1952), p367-369
Maxwell (1881). *Elementary Treatise on Electricity.* Oxford, England: Clarendon Press.
Ochs, E., Gonzales, P., Jacoby, S. (1986) *"When I come down I'm in the domain state":grammar and graphic representation in the interpretive activity of physicists*. In E. Ochs, E. Schegloff, & S. Thompson (Eds.) *Interaction and grammar.* Cambridge: Cambridge University Press.
Paatz, R., Ryder, J., Schwedes, H., Scott, P. (2004) *A case study analysing the process of analogy-based learning in a teaching unit about simple electric circuits*. International Journal of Science Education. 26(9):1065-1081
Petrie, H.G. & Oshlag, R.S. (1993). *Metaphor in Education*. In A. Ortony (Ed.), *Metaphor and Thought, Second Edition.* New York: Cambridge University Press.
Podolefsky, N., Adams, W., Finkelstein, N. (2004). *Analogical Scaffolding of Abstract Ideas in Physics.* Poster presented at the 2004 Physics Education Research Conference.
Redish, E.F. (2003) *Teaching Physics with the Physics Suite*. John Wiley & Sons, Inc.
Reiner, M., Slotta, J. D., Chi, M. T. H., & Resnick, L. B. (2000). Naïve physics reasoning: A commitment to substance-based conceptions. Cognition and Instruction, 18, 1-34.
Sandifer, C. (2003). *Spontaneous Student-Generated Analogies.* Proceedings of the 2003 Physics Education Research Conference.
Schwartz, D.L. (1993). *The Construction and Analogical Transfer of Symbolic Visualizations*. Journal of Research in Science Teaching. 30(10):1309-1325
Summers, M., Kruger, C., Mant, J. (1997). *Teaching Electricity Effectively: a research-based guide for primary science*. Published by the Association for Science Education.
Sutton, C.R. (1978). *Metaphorically Speaking: The role of metaphor in teaching and learning science.* Leicester University School of Education Occasional Papers
Taylor, J.R. & Zafiratos, C.D. (1991). *Modern Physics for Scientists and Engineers*. Prentice-Hall, Inc. Englewood Cliffs, New Jersey.
Wieman, C. Website location: http://spot.colorado.edu/~cwieman/Bosenova.html