Analogies: a key to understanding physics

Friedrich Herrmann (Chairman)
Karlsruhe Institute of Technology, Germany, f.herrmann@kit.edu

Wu Guobin
University of Shanghai for Science and Technology, China, wugb6688@126.com

Michael Pohlig
Karlsruhe Institute of Technology, Germany, pohlig@kit.edu

Hans Fuchs
Zürcher Hochschule für Angewandte Wissenschaften, Winterthur, Switzerland, hans.fuchs@zhaw.ch

Michele D'Anna
Liceo cantonale, Locarno, Switzerland, danna@liceolocarno.ch

Joel Rosenberg
Lawrence Hall of Science, U.C. Berkeley, jrosenberg@berkeley.edu

Introduction

Friedrich Herrmann

What is an analogy? In physics, by analogy we mean that two or more subfields can be described by means of the same mathematical structure. Any analogy can be resumed in a table that can be seen as a kind of dictionary. The entries of this dictionary are:

physical quantities
relations between these quantities
physical phenomena
words that describe the phenomena
models
technical devices
particles
fields
…

When teaching we often use analogies: between the electric and the magnetic field, between a capacitor and a coil, between sound waves and electromagnetic waves, between translational and rotational movements, between Newton's law of gravitation and Coulomb's law. However, there are also dormant analogies. No profit is taken of them. And this profit could be considerable.

We shall present a far-reaching analogy between four sub-fields of science: mechanics, electricity, heat and chemistry. Thus, our dictionary is quadrilingual.

The analogy is based on the fact that each of these scientific domains has its own characteristic extensive or substance-like quantity: momentum (mechanics), electric charge (electricity), entropy (heat) and amount of substance (chemistry) [1,2,3,4,5]. The analogy can be extended to phenomena and processes that are related to the transmission and storage of data [6,7].

The advantages of using this analogy are:

– The physics curriculum is more compact;
– physics is easier to understand;
– the barrier to neighboring disciplines is lowered.

Physics courses based on this analogy have been developed for all levels of education: Elementary School [8] Junior High School [9], Senior High School [10] and University [11,12]. Moreover, there are Web based courses that take advantage of the analogy [13,14]. In recent years, the approach had a substantial impact on official curricula.

Courses have been tested and are now applied in several countries. Just now a test phase is beginning in China.

Wu Guobin from the University of Shanghai for Science and Technology is a key person for introducing the *Karlsruhe Physics Course* in China.

Michael Pohlig is a teacher in Karlsruhe. He also gives lectures for future teachers at the Karlsruhe Institute of Technology.

Hans Fuchs is a Professor at the Zurich Institute for Applied Science. He is the Author of several text books.

Michele D'Anna is a teacher and teacher educator at Locarno, Switzerland. He is developing an integrated science course.

Joel Rosenberg is actually working at Lawrence Hall of Science at Berkeley, USA. He is working on a project for energy education.

Friedrich Herrmann is the coordinator of the *Karlsruhe Physics Course* project.

Literature:

[1] G. Falk, F. Herrmann, G. Bruno Schmid, "Energy forms or energy carriers?," Am. J. Phys. 51, 1074 –1077 (1983).

[2] G. Bruno Schmid, "An up-to-date approach to physics," Am. J. Phys. 52, 794 – 799 (1984).

[3] F. Herrmann and G. Bruno Schmid, "Analogy between mechanics and electricity," Eur. J. Phys. 6, 16-21 (1985).

[4] F. Herrmann, "Eine elementare Einführung in die Physik des Drehimpulses," MNU 39, 274-282 (1986).

[5] F. Herrmann, "The absorption refrigerator as a thermal transformer," Eur. J. Phys. 30, 331-336 (2009).

[6] F. Herrmann, P. Schmälzle and G. Bruno Schmid, "Information and its carriers," Phys. Education 20, 206-221 (1985).

[7] F. Herrmann and G. Bruno Schmid, "An analogy between information and energy," Eur. J. Phys. 7, 174-176 (1986).

[8] G. Falk and F. Herrmann, *Das Energiebuch* (Hermann Schroedel Verlag, Hannover, 1981).

[9] F. Herrmann, *Der Karlsruher Physikkurs, Ein Lehrbuch für die Sekundarstufe I* (Aulis, Stark-Verlagsgesellschaft, Freising, 2010) (free English version at:
http://www.physikdidaktik.uni-karlsruhe.de/index_en.html)

[10] F. Herrmann, *Der Karlsruher Physikkurs, Ein Lehrbuch für die Sekundarstufe II* (Aulis, Stark-Verlagsgesellschaft, Freising, 2010)

[11] G. Job, *Neudarstellung der Wärmelehre* (Akademische Verlagsgesellschaft, Frankfurt am Main, 1972)

[12] H. Fuchs, *The dynamics of heat* (Springer Verlag, New York, 1996)

[13] H. Fuchs, *Physics as a system science,* http://www.zhaw.ch/~fusa/PSS_VLE_C/index.html

[14] W. Maurer, *Physik der dynamischen Systeme*, http://www.pegaswiss.ch/

Origin of Analogical Reasoning in Physics

Hans U. Fuchs

Analogical reasoning is a form of figurative thought. Its precise meaning is very much subject to what philosophical stance one might take. Traditionally, analogy, like metaphor, is considered more of an embellishment of language than a serious (scientific) form. More recently, however, analogy has been recognized in cognitive science and cognitive linguistics as a fundamental and indispensable form of thought underlying much of human creativity.

Here, a definition of analogy motivated by recent advances in cognitive linguistics and in research into conceptual structures in continuum physics is presented. In this approach, analogy derives from the fact that human figurative thought leads to structuring of different phenomena with the help of the same recurring experiential gestalts, called Force Dynamic Gestalts (FDGs). FDGs are structured on the basis of image schemas (i.e., recurring patterns of experience or experiential gestalts) that are projected metaphorically onto objects of human thought. The basic aspects of FDGs created in this manner are quantity, quality (intensity) and force (or power). By employing FDGs, different phenomena are made similar to the human mind.

This similarity is made use of in analogical reasoning. The best known example of this form of analogy is Sadi Carnot's comparison of heat engines with waterfalls. Here, quantity (of fluid) is projected onto heat whereas level differences (differences of intensity) and power of a fall of fluid become temperature differences and power of heat, respectively.

Schematic Structure, Metaphor, and Roots of Analogy

Analogies are the result of a creative process. Cognitive science in general, and cognitive linguistics in particular, have taught us that thought is *figurative*: we use recurring experiential gestalts to structure our understanding of the world [1,2,3,4]. When the same structures (commonly *image schemas* [5,6,7]) that result from the embodied nature of our mind are *metaphorically projected* onto different phenomena, the human mind sees these different phenomena as *similar*. Such similarities are exploited in the production of *analogy* [8]. As a consequence, similarity is the result of this creative process, it is not preexisting out there in nature independently of the human mind and used post hoc to express an analogy.

To give an example, if we speak of *anger*, we use a schema called FLUID SUBSTANCE to describe and reason about aspects of this phenomenon. We may say that anger grew in him, that there is a lot of anger present in this group of people, that he passed his anger on to others, etc. At the same time we conceptualize of the intensity of anger: steaming anger, mild anger, etc., which makes use of the SCALE or VERTICALITY schema (the intensity of anger is high or low). The use of these schemas for phenomena that, by themselves, have nothing to do with fluid substances or verticality, is called a metaphoric projection (see Fig. 1).

Since we use the same schemas to conceptualize other phenomena such as pain, justice, light, fire, etc., these phenomena obtain a degree of similarity in the human mind (see Fig. 1) where the similarity is one of conceptual structure. The mapping of this structure from one field to another is called analogy. [8,9]

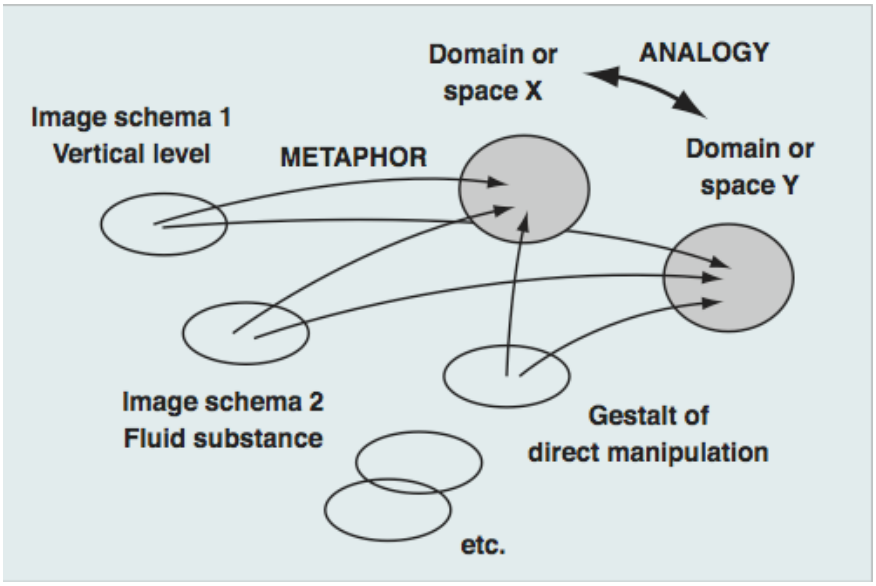

Fig. 1. The creation of similarity as a result of the metaphoric projection of a small number of image schemas upon different phenomena. This apparent structural similarity allows structure mapping—a general form of analogy. [8]

Force Dynamic Gestalt

One of the most pervasive experiential gestalts created in the perception of complex phenomena (justice, heat, anger, electricity, motion…) is what I call Force Dynamic Gestalt (FDG). [8] We first perceive these phenomena as wholes, then we begin to differentiate them, i.e., we create aspects. This differentiation happens more or less unconsciously; only when we begin to reflect upon our understanding of these phenomena do we become aware of the common aspects of the FDG. Natural language demonstrates that we use three figures to structure the gestalt [10]:

1. Quality or intensity
2. Quantity or size
3. Force or power

There are additional (sub-)structures. Essentially, several or all of the schemas identified by Leonard Talmy [11] in his theory of force dynamics (hindering, causing, letting, balance…) are employed. Furthermore, schemas such as the CONTAINER schema are used to extend the conceptualization of the FLUID SUBSTANCE schema (substances are contained somewhere, and they flow into and out of these containers).

As an example, consider how we speak (and according to cognitive linguistic, how we reason) about the phenomenon of justice. Here are some common expressions:

- *Quality, intensity, level*

  I have always found that mercy bears richer fruits than strict justice. (A. Lincoln)

- *Object, quantity, (fluid) substance*

  Justice denied anywhere diminishes justice everywhere. (Martin Luther King, Jr.)

- *Force or power*

  The healing power of justice.

The FDG which I have identified in the examples presented here can be seen to exist in our stories that make up our culture. As we will see, science is part of this culture.

Image Schemas and Other Schematic Structures

As mentioned before, (image) schemas play a fundamental role in embodied understanding [5,6,7]. The concepts of *quality* (intensity…), *quantity* (object, substance…) and *force* (power) originate in recurring experiences that lead to the formation of *image schemas* and other basic experiential gestalts. For us, the most important are:

- Scale and verticality
- Object, (fluid) substance
- Direct manipulation

There are many more, and their form, meaning and status in theories of the human mind are subject to intense current research [7].

Application of the Theory of the FDG to Physics

If we consider macroscopic physics in the form of a theory of continuous processes (continuum physics, [12-14]), we can identify the same basic structure of human conceptualization, i.e., the Force Dynamic Gestalt, that appears in the field of human interactions as well [9]. Take the phenomenon of electricity where we speak of a quantity of electricity (charge) being contained in elements and flowing from element to elements. The intensity of electricity, i.e., the difference of the electric potential between different elements is considered the driving force for the flow of charge. Electricity can be used to drive other processes (motion, heat, chemical change), it obviously can effect change. We construct a measure of the power of electricity to conceptualize and quantify this aspect of causation. Naturally, the power of a process is related to the quantity flowing through a given potential difference [15: Chapter 2].

The same structure of reasoning is employed in fluids, chemistry, motion, and heat [15,16-21]. In summary, the concepts of *quality* (intensity…), *quantity* (object, substance…) and *force* (power) are rendered in the form of the concepts of *potential difference*, *fluid substance*, and *energy*:

- Scale and verticality: POTENTIAL
- Object, (fluid) substance: FLUID SUBSTANCE
- Direct manipulation: ENERGY

Reasoning based upon these figurative structures leads to a feeling for the *relation* between the three. For an early and important example of this conceptual structure, let us discuss Sadi Carnot's thermodynamics.

Sadi Carnot: The Power of Heat

In the introduction to his book, *Reflexions sur la puissance du feu*, Carnot gave a vivid description of how we can understand thermal processes [22]. Here is a short excerpt:

> *Réflexions sur la puissance motrice du feu.* D'après les notions établies jusqu'à présent, on peut comparer avec assez de justesse la puissance motrice de la chaleur à celle d'une chute d'eau […]. La puissance motrice d'une chute d'eau dépend de sa hauteur et de la quantité du liquide; la puissance motrice de la chaleur dépend aussi de la quantité de calorique employé, et de ce qu'on pourrait nommer, de ce que nous appellerons en effet la hauteur de sa chute, c'est-à-dire de la différence de température des corps entre lesquels se fait l'échange du calorique.

Clearly, this is the FDG of thermal processes, with the aspects of quantity, intensity, and power of heat well differentiated [15: Introduction].

The Concept of Power

Carnot's thermodynamics can be used to introduce the concept of power in a general manner. Waterfalls takes the role of a physical archetype that can be employed in every field of macroscopic physics. Contained in the image is the formal result that the power of a process (here, the power of a fall of water) equals the product of the flow of the proper fluid substance (here, water) and the difference of levels (here, the difference of the gravitational potential) through which the substance flows (see Fig. 2).

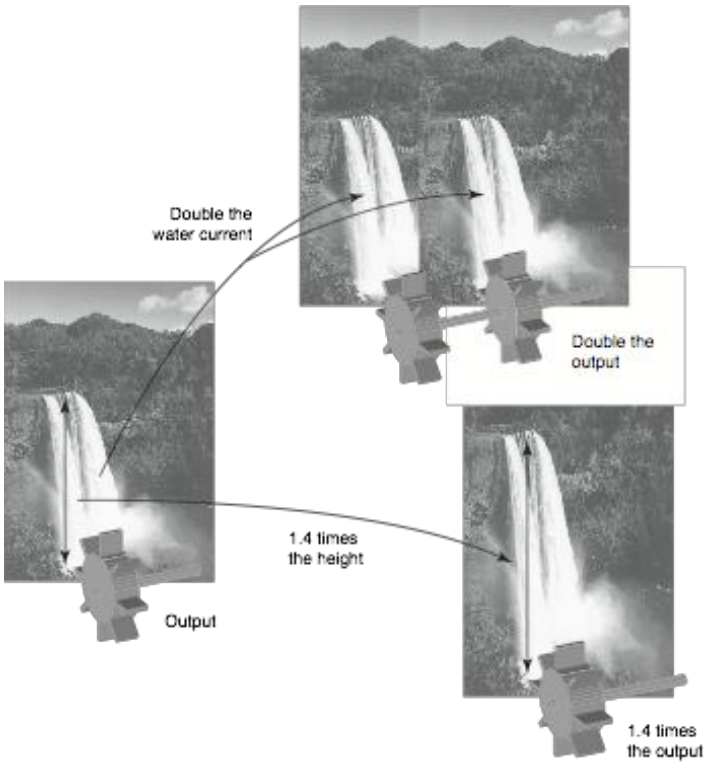

Fig. 2. The power of a fall of water equals the product of the current of water (mass) and the difference of the levels (gravitational potentials) through which the water falls. Figure taken from [23].

Summary

To summarize the foregoing, the fact that we humans perceive phenomena in the form of the *Force Dynamic Gestalt* allows us to compare different processes in a particular manner. Perception in the form of an FDG leads to the formation of a conceptual structure for a particular range of phenomena. This structure consists of the aspects of the gestalt among which the three most prominent are *intensity*, *quantity*, and *power*. The aspects arise out of a set of tools of thought which is made up of image schemas and other elements of figurative (embodied) understanding. The projection of a schema upon a particular phenomenon is called a metaphor that leads to examples of linguistic metaphoric expressions.

To give a prominent example, we conceptualize of thermal phenomena in terms of the *intensity of heat* (temperature of temperature differences), *quantity of heat* (entropy), and *power of heat*.

Since the same structure is employed to conceptualize vastly different phenomena, these become structurally similar to the mind's eye. As a result we can map the structure of one field upon another. In physics, this leads to a particular form of structure mapping, i.e., analogical reasoning where the structures of theories of phenomena such as fluids, electricity, heat, motion, and chemical

change are directly compared (see Fig. 3). The structure that is mapped is that of the Force Dynamic Gestalt.

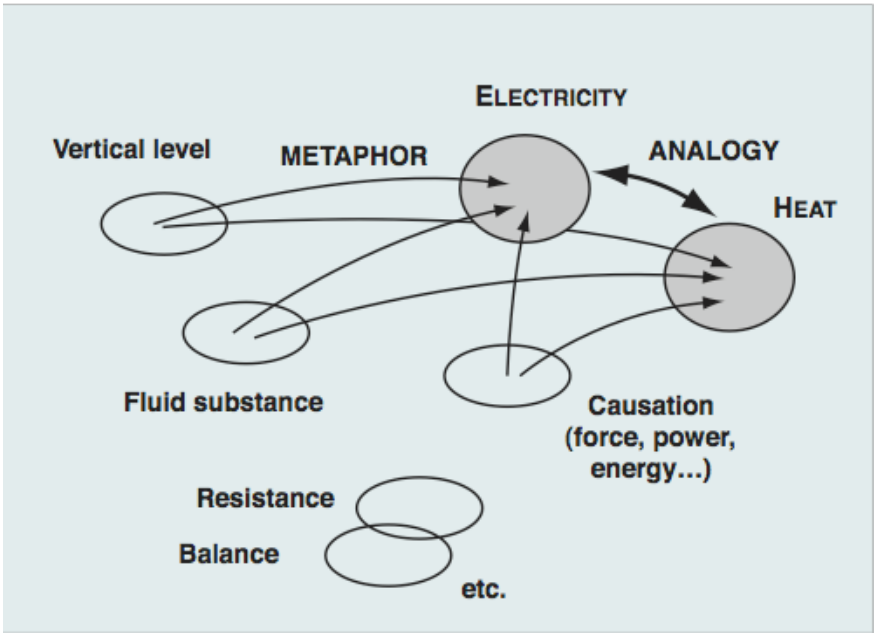

Fig. .: Applying the same FDG with its metaphoric projections to different physical phenomena leads to analogical structures (the metaphoric structure of one subject can be mapped upon another field).

Literature:

[1] Arnheim R. (1969): *Visual Thinking*. University of California Press. Berkeley, CA.

[2] Lakoff G. and Johnson M. (1999): *Philosophy in the Flesh: The Embodied Mind and Its Challenge to Western Thought*. Basic Books, New York, NY.

[3] Johnson M. (2007): *The Meaning of the Body*. The University of Chicago Press, Chicago.

[4] Gibbs R. W. (1994): *The Poetics of Mind. Figurative Thought, Language, and Understanding*. Cambridge University Press, Cambridge UK.

[5] Johnson M. (1987): *The Body in the Mind*. The Bodily Basis of Meaning, Imagination, and Reason. University of Chicago Press, Chicago.

[6] Lakoff G. (1987): *Women, Fire, and Dangerous Things. What Categories Reveal about the Mind*. University of Chicago Press, Chicago.

[7] Hampe B. (2005): *From Perception to Meaning. Image Schemas in Cognitive Linguistics*. Mouton de Gruyter, Berlin.

[8] Fuchs H. U. (2007): From Image Schemas to Dynamical Models in Fluids, Electricity, Heat, and Motion. An Essay on Physics Education Research. Zurich University of Applied Sciences at Winterthur (https://home.zhaw.ch/~fusa/LITERATURE/Literature.html).

[9] Gentner D. (1983): Structure Mapping: A Theoretical Framework for Analogy. Cognitive Science 7, 155-170.

[10] Fuchs H. U. (2006): System Dynamics Modeling in Fluids, Electricity, Heat, and Motion. GIREP Invited Talk, Amsterdam. In E. van den Berg, T. Ellermeijer, O. Slooten: *Modeling in Physics and Physics Education*. Proceedings of the GIREP Conference 2006, August 20-25, Amsterdam. (ISBN 978-90-5776-177-5)

[11] Talmy L. (2000): Toward a Cognitive Semantics. Volume I: Concept Structuring Systems. The MIT Press, Cambridge, Massachusetts.

[12] Fuchs H. U. (1997): The Continuum Physics Paradigm in physics instruction I. Images and models of continuous change. Zurich University of Applied Sciences at Winterthur.

[13] Fuchs H. U. (1997): The Continuum Physics Paradigm in physics instruction II. System dynamics modeling of physical processes. Zurich University of Applied Sciences at Winterthur.

[14] Fuchs H. U. (1998): The Continuum Physics Paradigm in physics instruction III. Using the Second Law. Zurich University of Applied Sciences at Winterthur.

[15] Fuchs H. U. (2010): *The Dynamics of Heat. A Unified Approach to Thermodynamics and Heat Transfer*. Second Edition, Springer, New York (First Edition: 1996).

[16] Falk G. and Herrmann F. (1981): *Das Energiebuch.* Hermann Schroedel Verlag, Hannover.

[17] F. Herrmann and G. Bruno Schmid (1985): Analogy between mechanics and electricity. Eur. J. Phys. 6, 16-21.

[18] F. Herrmann (2010): *Der Karlsruher Physikkurs*, Ein Lehrbuch für die Sekundarstufe I. Aulis, Stark-Verlagsgesellschaft, Freising (free English version at: http://www.physikdidaktik.uni-karlsruhe.de/index_en.html)

[19] F. Herrmann (2009): The absorption refrigerator as a thermal transformer, *Eur. J. Phys*. 30,331-336.

[20] Job G. and Herrmann F. (2006): Chemical potential – a quantity in search of recognition. *Eur. J. Phys*. 27, 353-371.

[21] Job G., Rüffler R. (2010): Physikalische Chemie. Vieweg und Teubner Verlag.

[22] Carnot S. (1824): *Reflexions sur la puissance motrice du feu et sur les machines propres a developper cette puissance*. Bachelier, Paris.

[23] Borer, Frommenwiler, Fuchs, Knoll, Kopacsy, Maurer, Schuetz, Studer (2010): *Physik – ein systemdynamischer Zugang*, 3. Auflage, h.e.p. verlag, Bern.