Sci & Educ
DOI 10.1007/s11191-010-9288-1

Principles Supporting the Perceptional Teaching of Physics: A "Practical Teaching Philosophy"

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Abstract This article sketches a framework of ideas developed in the context of decades of physics teacher-education that was entitled the "perceptional approach". Individual learning and the scientific enterprise are interpreted as different manifestations of the same process aimed at understanding the natural and social worlds. The process is understood to possess the basic nature of perception, where empirical meanings are first born and then conceptualised. The accumulation of perceived gestalts in the "structure of the mind" leads to structural perception and the generation of conceptual hierarchies, which form a general principle for the expansion of our understanding. The process undergoes hierarchical development from early sensory perception to individual learning and finally to science. The process is discussed in terms of a three-process dynamic. Scientific and technological processes are driven by the interaction of the mind and nature. They are embedded in the social process due to the interaction of individual minds. These sub-processes are defined by their aims: The scientific process affects the mind and aims at understanding; the technological process affects nature and aims at human well-being; and the social process aims at mutual agreement and cooperation. In hierarchical development the interaction of nature and the mind gets structured into a "methodical cycle" by procedures involving conscious activities. Its intuitive nature is preserved due to subordination of the procedures to empirical meanings. In physics, two dimensions of hierarchical development are distinguished: Unification development gives rise to a generalisation hierarchy of concepts; Quantification development transfers the empirical meanings to quantities, laws and theories representing successive hierarchical levels of quantitative concepts. Consequences for physics teaching are discussed in principle, and in the light of examples and experiences from physics teacher education.

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Published online: 22 August 2010

1 Introduction

This article reports a framework of ideas which forms the underpinnings of a physics teaching strategy named "*perceptional approach*". The framework was formed and utilised in the context of about 30-years development of physics teacher education within the Department of Physics at the University of Helsinki. It was founded on views about the nature of physics as a science and as a part of the human culture. These views had grown from my experiences as a research physicist, as a teacher of physics, and from a long participation in the national curriculum reforms.

Physics students have always struggled to grasp the idea of the empirical meanings of the physics formulae they use. In addition, students experience considerable difficulty in making conceptual sense of their laboratory exercises (Herron 1975; Kurki-Suonio 1984; Arons 1997). These problems are related to the unwarranted dominance of the blind use of mathematical manipulations in problem solving, the unbalance between empirical and theoretical aspects of physics as they are addressed in teaching, and the many practical problems of deficient understanding of physics flowing out from these very basic shortcomings.[1] The perceptional approach to physics teaching attempts to remedy this situation by recognising the importance of the pupil's perception of empirical meanings as the starting point for learning, rather than by offering them ready-made models of thought; and by recognising the importance of understanding the nature of physics as an empirical science, its relation to technology, its cultural dimensions, and, hence, its potentialities in the personality development.

The starting point and the underlying general view of the perceptional approach is based on the conception that perception plays a fundamental role in all learning. Understanding the principles of concept formation forms an essential basis for teaching. Concept formation is essentially based on the perception of empirical meanings of concepts. The idea of learning as the perception of gestalts has been suggested by many scientists; perhaps the most well-known proponent is Ernst Mach (1893/1960). In Finland similar ideas—probably influenced by Mach—about the nature of concepts as gestalts have been emphasised by Eino Kaila and Rolf Nevanlinna (Siemsen and Siemsen 2009).

The framework of ideas on which perceptional approach is based can be characterised as a "practical teaching philosophy". This indicates the nature of the framework as presented in this article; it is a tool for teacher education. The purpose is not only to develop and teach methods of teaching physics, but to offer the teachers a simple epistemological and psychophysical model, which can serve as a foundation for development of one's own teaching procedures. Moreover, the ideas are formulated in a way, which calls for

[1] Such problems are widely described in literature. Feynman (1985) gives (pp. 191–195) an account of his experience of Brazilian physics teaching. He concludes that 'no science is being taught in Brazil'. There are very illuminating pages dealing with the example of polarization of light on pp. 211–212. Of his physics class he says (p. 213): "…they could pass the examinations, and "learn" all this stuff, and not *know* anything at all, except what they had memorized". Also, on pp. 217–218 Feynman discusses how detrimental it is to discuss physics without reference to the experiments. In similar tone, Arons (1997) notes "we are merely cultivating blind memorization without comprehension … crushing our students into the flatness of equation-grinding automats. …We do not even give them a chance to begin to understand what "understanding" means". As a result "a great majority of university students of science and technology have no more understanding of the ideas involved than the seven-year-old…. They are unable to discriminate, what of knowledge they possess is based on evidence and understanding, and what consists of memorized, unsupported assertions", and continues to note that "This undermines their capacity to distinguish between jargon and knowledge….This condition is destructive of any understanding of nature, power and limitations of science."

discussion of the validity of the model and its possible applicability beyond physics. Such discussions can strengthen the confidence of the physics teachers on the significance of their work and encourage them to "think big" of it. This means appreciation of physics as science, its relations to other fields of science and to other school subjects, and to technology, as well as of the role of physics as an inseparable part of cultural history and its position in the field of human culture (compare with e.g. Bronowski 1973; Arons 1997; Holton 1973; Holton and Brush 2001), and, ultimately, realising the significance of the role of a physics teacher as a temporary guide of the pupil's life-long learning process. These dimensions of the framework were active in the teacher education, but closer discussion of them is beyond the scope of this article.

The basic ideas of the perceptional approach are simple in principle. Many of the basic tenets are familiar in one form or another from constructivist learning theory, gestalt-psychology and cognitively oriented views on learning. In this study, as in the practice of teacher education described here, these tenets were never deeply analysed to the level customary in the research literature. At the same time, this has been the strength and the weakness of the approach.

The practical orientation, which avoided a deeper analysis, rendered the basic ideas approachable for teachers and dispelled the antagonism that teachers very often harbour toward more formal academic research, which they seldom read or study. On the other hand, the casual and practical way of addressing the questions has rendered it difficult to communicate the fundamentals to researchers in the international field. However, from the point of view of the teaching developments, delving deeper into a more accurate or philosophical analysis of such terms as *perception*, *observation*, *gestalt*, *mind* and *nature* was never considered very important; the terms have served in a manner that was understandable for the teachers.

The active development of the perceptional approach has progressed through practical teaching. Efforts focused on the development of the teaching programme itself and the production of the necessary materials in Finnish. The first stage took place in late 1970s and early 1980s through involvement in the revision of the national secondary school syllabus and the related design of a textbook series for upper secondary high schools and, at the same time, through the design of physics courses for teacher education. These commissions, together with innumerable related invitations to discuss the ideas with in-service physics teachers, provided plenty of relevant material and ultimately led to the course entitled *Principles of Didactical Physics*. Until 1994, this course was the main "workshop" for the development and formulation of the principles of the perceptional approach. The participating in-service teachers offered a most useful coupling with the school whereby the ideas discussed could often be immediately tested in practice.

Another important project was the development of the three basic courses of physics for second-year university students. Application of the principles developed necessitated writing unique text-books for these courses, as well as developing proper lecture demonstrations (Andersson et al. 1989) and associated student laboratories (Hautala and Kurki-Suonio 1989). Finally, in the late 1990s a complementary education course for in-service physics teachers was arranged, as part of the national development project "Finnish Mathematical and Natural Science Awareness, 2002". Altogether, about 300 physics teachers of lower and upper secondary school (grades 7–12) and of vocational schools from all over Finland participated in the programme (for a description, see Lavonen et al. 2004; Jauhiainen et al. 2002). By the end of the millennium, the practices and principles of the perceptional approach to physics teaching were more or less established as a national physics programme for teacher education. The core components of the teaching programme were the four courses:

1. *Principles of Didactical Physics* (PDP), which introduced the theoretical principles of the perceptional approach.
2. *Conceptual Structures of School Physics*, which was designed to fill the gap between theory and laboratory practice and to provide a detailed discussion of PDP in all subfields of school physics.
3. *Planning of Perceptional Empiry* which provided training in the planning, design and practice of empirical observation and experiments to support the perceptional approach in school teaching (Kurki-Suonio 1999).
4. *History of Physics* course designed to provide the proper historical perspective and to compare the perceptional approach to conceptual development in the history of physics.

These courses have ever since formed the basis of physics teacher education in the Department of Physics, University of Helsinki; although they have undergone modifications and changes over the last decade, the basic tenets of the courses remain clearly discernible (see e.g. Koponen and Mäntylä 2006).

Due to different circumstances, the principles of the perceptional approach were never submitted to wider international discussion and evaluation. Only some elements of the approach were reported in English in conference papers. Lack of time and resources was an obvious reason. We also felt we were too far from a satisfactory final formulation. Moreover, that the principles proved useful in the school practice of the participants, was sufficient to convince us. In addition, preparing practical applications for teaching different subjects, which was considered more important than the research-based evaluation of the effects of the course, or dissemination of its basic ideas to the research community, proved to be an endless challenge. This article has been written as in an attempt, in some small measure, to rectify this shortcoming. What is discussed here covers the core ideas of the perceptional approach as it developed during the years 1973–2000.

Sections 2 and 3 sketch the general idea of structural perception as the basis of concept formation. Section 4 discusses the associated hierarchical development of the perception process itself. Section 5 identifies two generative factors of hierarchy, definitisation and generalisation, in formating the conceptual structure of physics, and discusses the consequent "two-dimensional" expansion of the conceptual hierarchy. Section 6 reports some experiences on introducing these principles in physics teacher education. A few problems of a general nature are highlighted together with examples of how the problems have been approached in the Finnish teacher education.

2 Perception and Gestalts

The underlying general view of the learning approach discussed here is based on the conception that perception plays a fundamental role in all learning. Originally, *perception* refers to sensory perception and is characterised as pattern recognition or identification of order in chaos. In this context, perception is interpreted generally as the creation of meanings (of observations and interpretations), an intuitive process in which non-conscious elements are essential. In what follows, mental products of perception are called *gestalts*,[2]

[2] In the beginning of twentieth century, gestalt psychologists endeavored to identify the principles through which sensory information is interpreted. These gestalt psychologists claimed that coherent perceptual experience is more than the sum of its parts and that objects are perceived as organised wholes, configurations or patterns—as *Gestalten*. To recognise an object, one must distinguish it from its ground. Gestalt

and the terms 'perception' and 'gestalts' are used in their common meaning, with no specific connotations connected to special branches of phenomenology or gestalt-psychology. Such broad usage of these terms is perfectly adequate for purposes of teaching and learning as discussed here. In practice, teachers have also appreciated such usage, as they often find the deeper analysis of these terms unnecessarily complicated and not illuminating.

2.1 Meanings First

The perceptional approach to teaching and learning advocated here is underpinned by two assumptions. These assumptions, which should be understood rather as chosen starting points than justified facts, are as follows:

1. Science and learning are manifestations of one and the same cultural process on two different levels.
2. Th*e learning process* and *the process of science* both share the basic nature of *perception.*

The first assumption views science as the natural continuation of learning, and learning as the origin of science [the position stated often by Dewey (1916, chap. 17; 1929a, b, chap. 8)]. Science consists of the learning processes of individuals, and learning involves sharing of the process of mankind. Learning means for the individual what science means for mankind: the search for knowledge and better understanding. Both learning and science endeavour to understand the unknown. While the "scientific community" is progressing on the frontier of the development of science, the individual advances on the frontier of his own process. Children, students and scientists are merely in different phases of their individual processes.[3] The second assumption essentially specifies the common nature of science and learning, as this article will discuss. This assumption is comparable to Dewey's view that science is the refinement of commonsense.

Awareness of meanings is the basis of *understanding*. Understanding physics means mastery of the empirical meanings of concepts representing "aspects" of nature. The meanings must be perceived before they can be *conceptualised,* as for example Hadamard (1945) has shown concerning science,[4] and Arons (1997) and Herron (1975) have

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Footnote 2 continued
laws of perception describe how elements tend to be perceived together: (1) proximity (elements occur closely in space or time), (2) similarity, (3) continuity, (4) closure (closed figures are perceived more easily), (5) part-whole relationship (the whole is greater than its parts), (6) common fate (elements seen moving together are perceived as belonging together (Gross 2005). Gestalts are related to the idea of schema and similar such constructs. Some researchers (e.g. Rowlands et al. 1999; diSessa and Sherin 1998) have studied learning by using the concept of schema, which they define as a mental representation of a set of related categories. With a somewhat similar purpose diSessa introduced the concept of "phenomenological primitives" (or "p-prims"), which are based on intuition and which must be appropriately organised and activated under various circumstances. These constructs share many similarities with the concept of gestalt introduced here.

[3] Hadamard (1945, p. 103) notes: "Between the work of the student who tries to solve a problem … and a work of invention (of a mathematician),… there is only … a difference of level, both works being of a similar nature."

[4] Hadamard (1945, chap. VI) discusses, in a passage titled *Words and Wordless Thought,* the relation of language and thinking. He opposes Müller's statement that "The idea cannot be conceived otherwise than through the word and only exists by the word." and agrees with Hamilton, who says that the "… Idea must necessarily precede the word." He also refers to sensations as a primary source of meanings, stating that "… if I remember lightning, I see in my mind the flash of light… and I should need an instant of reflection… if I

discussed concerning learning and teaching.[5] Consequently, *concepts* are representations of meanings, which emerge from the perception of the "aspects" in question.[6] Once the gestalt of an "aspect" is assimilated into our mental structure, we possess the primary understanding of it and can now further conceptualise it; the concepts inherit from their meanings the essentially intuitive nature of gestalt. *Conceptualisation* is the process, which ultimately furnishes us with linguistic terms and thus permits conscious discussion of the intuitively understood meanings.

This view of conceptualisation based on perception differs from the conventional textbook view in which treatment of a subject begins by providing *definitions* for the basic concepts of the area. Most textbooks then proceed by deductive reasoning on the basis of the definitions.[7] Such an approach involves the idea of a final definition as the exhaustive characterisation of the meaning of the concept. The image given then lures students to think that with such a definition, one could logically derive from it all possible occurrences, uses and applications of the concept.[8] Physics then appears as a mathematical science with axiomatic conceptual structures, where all possible statements concerning natural phenomena follow by logical necessity from the axioms. This background idea is clear, for instance, in those numerous texts where Newton's laws are called axioms of mechanics. In contrast to such definitional views, however, an obvious consequence of the gestalt nature of concepts is that final exhaustive definitions are impossible; any definitions of representative concepts necessarily have restricted validity. Concepts are always open for further extension of their meanings.

2.2 The Three-Process Dynamics of Perception

Perception arises from the interaction of nature and mind, where the human mind meets reality. The roles of the counterparts in this interaction can be identified: Nature produces signals which generate the sensual stimuli necessary for the formation of sensations. The "structure of the mind" has two opposite roles (Sects. 3.1–2): it defines one's mental capacity for perception, while restricting and regulating the nature of the possible gestalts

Footnote 4 continued
should wish the corresponding word to recur to me." In Appendix II, Einstein describes his own thinking as follows: "The words or the language … do not seem to play any role in my mechanism of thought. The psychical entities which seem to serve as elements in thought are certain signs and more or less clear images which can be 'voluntarily' reproduced and combined … Conventional words or other signs have to be sought for laboriously only in a secondary stage."

[5] Arons (1997) principle (p. 27) of "idea *first* and name *afterwards*" corresponds to the declaration "*Meanings first*" of the perceptional approach; he simply uses the term "percept" as a synonym for "gestalt".

[6] Einstein (1970) writes in his Autobiographical notes in p. 13: "The concepts…get "meaning," viz. "content," only through their connection with sense-experiences".

[7] Karvonen (1995) concludes in her linguistic thesis that "Textbooks take knowledge as given… a typical textual pattern is one that begins with a definition … the texts are deductive, they begin with finished presuppositions…. The texts do not make possible a process for the reader, let alone require it."

[8] James (1909) wrote: "Intellectualism in the vicious sense began when Socrates and Plato taught that what a thing really is, is told us by its definition. Ever since Socrates we have been taught that … the essences of things are known whenever we know their definitions. … The misuse of the concepts begins with the habit of … using them not merely to assign properties to things, but to deny the very properties with which the things sensibly present themselves. Logic can extract all the possible consequences from any definition, and the logician … is often tempted, when he cannot extract a certain property from a definition, to deny that the concrete object to which the definition applies can possibly possess that property."

as mental interpretations of the signals or as meanings of the observations. These actions occur simultaneously, intertwined into an inseparable whole. The interaction of nature and the mind can be analysed and discussed by idealising it as two opposite processes, here called the 'scientific process' and the 'technological process'.

The scientific process affects the mind and consists of the perception of meanings and the conceptualisation of observed aspects of nature. It aims to understand nature, and its products are gestalts, mental pictures, concepts, and conceptual structures representing perceived aspects of nature in our minds. It is driven by *scientific activity* which poses ontological questions about existing entities and phenomena as well as their properties and mutual relations.

The technological process affects nature. It aims at the fulfilment of any needs or wishes of any individual or group. Its products are new aspects of nature or artefacts and can be new entities produced, phenomena caused, or modifications of the properties of entities or phenomena. Since we are part of nature, this includes activities learnt and the adaptation of behaviour to the conditions of nature. *Technological activity* is practically oriented, enquiring about the significance of perceived entities and phenomena, their possible uses and applications as well as potential risks and hazards. Technological activity can be characterised as looking for problems to be solved by manipulating nature.

These two processes are embedded in the *social process,* which is understood to arise from the interaction of individual minds combining them into a community as the other counterpart of the interaction with nature. The social process becomes defined by its aim: mutual agreement. This includes all elements of the other processes, their aims and procedures, as well as meanings, interpretations and ways of representation. It also plays the important role of bringing background motivations, needs and wishes to the conscious level for common evaluation and approval. The social process proceeds by communication, involving what is often called 'negotiation about meanings' in constructivist learning theory.[9]

2.3 Intertwining of the Three Processes

The three processes form a dynamical whole. In this context, the focus is on the scientific process, which is responsible for the creation of gestalts, concepts and conceptual structures. However, the other two processes play such an essential role that one can speak of a three-process dynamic of perception. Due to this dynamic, the meanings of all physical concepts also have, in addition to their scientific core meanings, technological and sociological dimensions, which are essential to understanding them. In particular, as a consequence of the technological process, every perceived gestalt involves a practical meaning right from the beginning. When speaking of empirical meanings, the inclusion of these elements should be implicit.

The scientific process requires the intervention of the technological process. Merely "posing questions" to Nature is insufficient. More active intervention is necessary to perceive messages in the noise inherent in natural phenomena. Even primary sensory perception requires an inquisitive mind. Nature, on her own initiative, provides no answers or speaks nonsense. *Nature must be forced to answer.* The modification of nature through the careful design of experiments is necessary in order to let Nature do nothing but realise

[9] The constructivist learning theory discusses negotiations over meanings in a manner very similar to that of a dialectical process between the individual mind and socially agreed conceptions (see e.g. Tobin 1993).

the phenomenon considered by concentrating on the aspect in question,[10]—Kant saw this as the essential Galilean breakthrough in the history of science (Kant 1787/1933, p.20). The design of a new experiment always encounters problems to be solved. Solving them leads to new experimental procedures and thus makes possible more and more accurate quantitative research and new controlled experiments. Although the problem setting of a research laboratory pursuing basic research is governed by the aims of the scientific process, the technological process dominates its everyday workings.

At the same time, new artefacts produced by the technological process are submitted to the scientific process for understanding. And as by-products of the technological process, we learn to know, produce and control previously unknown natural phenomena. Phenomena created by technology have often been of decisive significance as starting points for new conceptual ideas. We know, for instance, the importance of Archimedes' machines to his laws of statics and hydrostatics, the revolutionary scientific development launched by Volta's invention of the electric couple, and the significance of the invention of the heat engine to the discovery of the idea of the second law of thermodynamics. Other corresponding examples can be found in abundance in, for instance, the history of electrodynamics and electronics.

On the other hand, progress in the technological process is based on the scientific process. The development of technological products and procedures is based on understanding the entities, phenomena, properties, quantities and laws involved. At the same time, the simultaneous further development of their conceptual understanding becomes necessary. When new phenomena are perceived they pose immediately the problem of their usage. The discovery of new natural laws creates opportunities for new technological inventions.

3 Accumulation of Conceptual Understanding

Conceptual understanding originates with the formation of gestalts. This requires continuous and repeated sensations; and co-sensations by different senses. Before the gestalt is perceived as a mental representative of an entity or phenomenon, the sensations must be experienced as both mutually consistent and supportive of each other.[11] In the perception of warm and cold, for example, or tastes and smells, it is essential that these gestalts of properties be associated with the gestalts of certain entities and phenomena, such as mother, food, touching, and eating. Properties perceived do not "float in the air", but are properties of something. A body is not just a body, but exists somewhere and in some relation to other bodies, and has different properties, which can be perceived by different senses; moreover, the properties exist in relation to other properties.

[10] This remark can be compared with Polykarp Kusch's notion in his Nobel lecture in 1955, where he remarks that: "Our early predecessors observed Nature as she displayed herself to them. As knowledge of the world increased, however, it was not sufficient to observe only the most apparent aspects of Nature to discover her more subtle properties; rather, it was necessary to interrogate Nature and often to compel Nature, by various devices, to yield an answer as to her functioning. It is precisely the role of the experimental physicist to arrange devices and procedures that will compel Nature to make a quantitative statement of her properties and behavior" (Kusch 1955).

[11] Einstein (1970) writes in his Autobiographical notes in p. 7: "What, precisely, is "thinking"? When, at the reception of sense-impressions, memory-pictures emerge, this is not yet "thinking." And when such pictures form series, each member of which calls forth another, this too is not yet "thinking". When however, a certain picture turns up in many such series, then—precisely through such return—it becomes an ordering element for such series, in that it connects series which themselves are unconnected. Such an element becomes an instrument, concepts."

3.1 Structural Perception

There is a "*groping phase*"[12] of longer or shorter duration before the different elements of sensations fit together and with the pre-existent mental structure. An intuitively sufficient degree of consistency results in the formation of a perceived gestalt and its inclusion in the mind as a new structural element. The *gestalts,* therefore, *have a structural nature* right from the beginning. Thus perception builds up the "structure of mind". Then, the gestalts also become elements of further perception. This leads to s*tructural perception.* The already understood gestalts become building blocks for new structural gestalts. Thus, the accumulation of the "structure of the mind" entails not only the extension, but—even more essentially—the formation of a structural hierarchy of empirical meanings, which in conceptualisation gives rise to a corresponding conceptual hierarchy.

In this way, the scientific process leads to a *hierarchically layered structure of knowledge;* new layers are based on previous ones.[13] Concept formation on a higher layer involves the identification of the structural relations of lower-layer concepts and the perception of structural gestalts due to these relations. While the individual concepts possess a gestalt nature inherited from the empirical meanings, the conceptual structures themselves are also based on structural empirical meanings and have the gestalt nature. The structural relationships belong to the gestalts and themselves constitute empirical meanings.

The mental counterpart of the perceptual interaction has, thus, a cumulative nature and an expanding hierarchical structure. This, effectively, means the *accumulation of conceptual understanding*. The potentialities for further perception expand with the progress of the process. In learning by perception, the ability to learn also improves with progress: the more one learns and understands the better become one's facilities to learn more.

3.2 Permanence of Gestalts

Knowledge created by perception is by nature *permanent*. The meanings of "warm" and "cold" will always remain "warm" and "cold" in the mind. Once perceived, a "stone", "chair", "ball", "fall", "round", or "red", will for the perceiver permanently remain a "stone", "chair", "ball", "fall", "round", "red". The same holds true for more advanced structural concepts. Gestalts, perceived and assimilated as elements of one's "structure of the mind", become parts of one's developing understanding. The meanings of mass, force, field, and the causal relationships between interaction and motion, once understood through perception, will remain stable in one's mind, and the gestalts of charge, electric current, magnetism and their connections, once perceived, will remain permanent elements of one's developing world picture. This does not prevent the gestalts fading or the structures rusting with time, as any structures would if left unmaintained. But this differs from losing pieces from an unconnected heap of separate facts collected by a rote learning, even though

[12] This is related to Hadamard's (1945) description of a mainly unconscious "incubation stage" and the preceding "preparation stage" of conscious attempts to "solve a problem".

[13] In his book *The Process of Learning*, Jerome Bruner (1960) hypothesises that "any subject can be taught effectively in some intellectually honest form to any child at any stage of development" (p. 33). He argues the hypothesis with the notion of a spiral curriculum: "A curriculum as it develops should revisit this basic idea repeatedly, building upon it until the student has grasped the full formal apparatus that goes with it" (p. 13). The perceptional approach to teaching physics can be viewed as a roadmap to a spiral curriculum that systematically takes into consideration the hypothesis of an intellectually honest form of teaching a subject at any level.

details learnt by heart can be extremely stable.[14] This permanence enhances both roles of the "structure of the mind" (Sect. 2.2). Not only is it important for further learning, but the *regulative power* of mind is also enhanced. This leads to difficulties when new empirical evidence would require the modification of one's conceptions.

3.3 Stepwise Development of Empirical Meanings

Empirical meanings are always open to further development. The normal development of the concepts of physics entails, for any particular concept, a chain of successive meanings or a net of interconnected meanings all valid in certain areas of phenomena.[15] In learning physics, perception of the gestalt of any particular aspect of nature proceeds in steps. Each successive step involves a necessary groping phase that precedes the formation of a new, more advanced gestalt. The resulting more developed meanings of the aspect of nature include definitisations, extensions, generalisations, or some other modifications of the established meanings. Each "intermediate" gestalt in this development, however, remains stable with regard to its perceived meaning.

The nature of empirical meanings as gestalts also concerns all conceptual structures. In view of the perception process, ordinary theories of physics,[16] such as classical mechanics, electrodynamics or quantum mechanics are each, as a whole, highly structural gestalts, and the permanence of gestalts also concerns the theories. For instance, Newtonian mechanics is a permanent gestalt. Lagrangian mechanics, Hamiltonian mechanics, even quantum mechanics and the theory of relativity, in their different successive formulations and extensions, represent further phases in the step-by-step development of our understanding of the phenomenal area of motions and interactions. However, they do not invalidate the original justification of Newtonian mechanics. The long groping phases of these steps in conceptual evolution, as they appear in the history of physics, are a natural consequence of the highly structural nature of the gestalts involved.

Conventionally, physics is thought to encompass separate classes of empirical and theoretical quantities. The theoretical quantities would be defined as structural combinations (algebraic expressions) of empirical and/or other theoretical concepts. The meanings of the theoretical concepts would then merely stem from these structural relationships. Within the framework of concept formation as a process of perception, concepts can be said to possess theoretical meanings defined by their positions in the conceptual structure of the theories (*i.e.* by their relations with the other elements of the theory). Single concepts, such as *time, position, mass, force* or *kinetic energy,* possess different positions in different theories. Each theory also comprises certain basic quantities, in terms of which models within the theory are formulated in order to enable predictions concerning some derived quantities. For instance, in Newtonian mechanics, mass and force are basic quantities, while momentum and energy belong to derived quantities. In Lagrangian and

[14] The notion of the permanence of gestalts owes to their origins in intuitive understanding. As is well known, understanding obtained by intuition or intuitively considered right and correct is a very stable mental construct. The results of studies concerning students' conceptions have convincingly shown that such constructs are persistent and resistant to changes, and are very difficult to change through instruction (e.g., Chi et al. 1994). Intuitive common-sense conceptions are persistent because they adequately explain everyday observations of the physical world (see e.g. Posner et al. 1982).

[15] Arons (1997) writes (p. 354) that "… scientific terms go through an evolutionary sequence of redefinition, sharpening, and refinement as one starts at a crude, initial, intuitive level, …."

[16] This formulation emphasises the exclusion of hypotheses, fictitious conceptual constructs, and theoretical ad hoc suggestions for interpretation without a perceptional foundation, often called "theories".

Hamiltonian mechanics the roles of energy and force are inverted in what can be called a "revolution of invariants". The basic role of energy is further transferred to quantum mechanics, while force no longer plays a role. The theoretical meanings of the concepts are theory-specific, but the empirical meanings, such as the meanings of time, mass and force as measures of duration or a time interval, inertia of a body or particle, and vector strength of interaction, respectively, are theory-independent. Therefore, the empirical meanings form the common core of all the theoretical meanings, the basis of any empirical predictions concluded from the theory.

A characteristic of concept formation in physics is that structural relationships of perceived gestalts lead to the perception of structural gestalts, which motivates the adoption of new concepts. Such concepts are often labelled theoretical terms. Force and energy are typical examples. In view of the perceptional approach, the meanings of all concepts are first and foremost empirical. But concepts are developing and new concepts are perceived as structural gestalts formed by earlier concepts. Thus, in the development of meanings, the degree of structurality gradually increases. This can also be interpreted as increasing theoreticality, but the basic empirical nature of the concepts remain.[17]

4 Structurisation of Perception into a Methodical Cycle

The accumulation of structural gestalts and conceptual structures in the "structure of the mind" can also be seen as the interaction of experimental and theoretical knowledge affecting and transforming each other. Here, "*theory*" refers to theoretical knowledge and theoretical activity in general (Bradley 1975), while "*empiry*", its counterpart, is used to refer to experimental knowledge and experimental activity. The elements of the "structure of the mind" grow through successive hierarchical stages of *theory*,[18] from gestalts and mental images to qualitative and quantitative concepts, conceptual structures and causal models, and up to theories. Correspondingly, *empiry* grows hierarchically from sensation to conscious observation, qualitative and quantitative experimentation, and up to organised experimental research projects.[19]

[17] Neglecting the initial empirical meanings of quantities as perceivable properties of entities and phenomena seems to be a general problem in physics teaching. For instance, force, energy and work are often introduced on the basis of theoretical considerations only. Force is regarded as a theoretical concept which cannot be learned until the Piaget level of formal operations is reached. According to Feynman et al. (1963, chap. 4.1), energy is a mathematical concept: "There is a law governing all natural phenomena … called the *conservation of energy* …. That is a most abstract idea, because it is a mathematical principle;… it is just a strange fact that we can calculate some number and when we finish watching nature go through her tricks and calculate the number again, it is the same…. However, there are formulas for calculating some numerical quantity, and when we add it all together it gives … always the same number. It is an abstract thing in that it does not tell us the… *reasons* for the various formulas." In addition, the never-ending discussion about the nature of mass, force and energy is based largely on highly theoretical considerations without reference to the initial empirical meanings.

[18] Note the double meaning of "theory" in the context of concept formation. Firstly, it refers generally to the theoretical nature of all concepts regardless of their hierarchical position. All concepts are "theory" as the opposite of "empiry". Secondly, in its specific meaning, "theory" refers to a coherent conceptual structure formed by certain basic laws so extensive that a "theory" is understood to constitute a common explanatory basic model of a whole class of phenomena. For instance, Newtonian mechanics and Maxwellian electrodynamics are theories in this sense.

[19] The basic form and direction of progress in the conceptualisation process as outlined here is very common and has its roots in 19th century conceptions of the structure of science. Similar conceptions are also recognisable in many more recent logical reconstructions of science (e.g. in logical empiricism). These

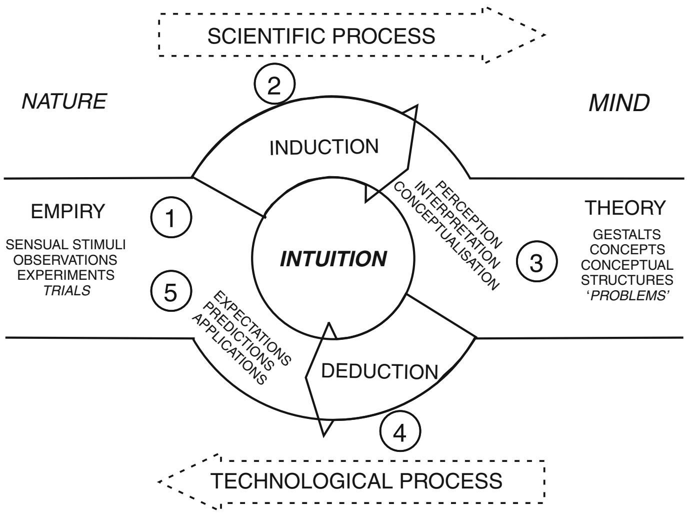

Fig. 1 Differentiation of perception into a methodical cycle

4.1 The Procedures Running the Cycle

The intuitive interaction of nature and mind is structured by the introduction and hierarchical development of *conscious procedures,* and is differentiated into a methodical cycle beginning with the phases: 'empiry'—'induction'—'theory'—'deduction', and then beginning again with empiry. A schematic representation of this cycle appears in Fig. 1. The cycle involves *experimental* procedures for the design of experiments to collect more accurate experimental data with ever greater efficiency (1), and *theoretical procedures*, largely based on mathematical methods and computing, to aid in the perception of meanings; that is treatment and interpretation (2) of the experimental results for the consequent formation of concepts and conceptual structures (3); and for producing predictions (4) to be tested empirically in further experiments (5) that yield new data, which then lead to further subsequent loops in the cycle.

Induction and *deduction* are operations acting in opposite directions between empiry and theory; to be understood here as normal elements of everyday logic[20] in making inferences and drawing conclusions, rather than as the formal logical procedures discussed in the philosophy of science.[21] The perception of gestalts on the basis of sensual stimuli

Footnote 19 continued
roots are discussed in more detail by Koponen and Mäntylä (2006) in their study as well as in references therein.

[20] This is one aspect of the first assumption of Sect. 2.1 and has often been expressed more or less explicitly in the literature. According to T. H. Huxley, "science is nothing but well organized layman reason". Einstein has said that "scientific reasoning is nothing but more accurate natural thinking". Referring to E. Kaila, R. Nevanlinna states that "scientific thinking is nothing but refined everyday thinking".

[21] It is often necessary to ignore the strict constructs of formal logic and analytical philosophy if such ideas as "induction", "deduction" and "inference" are used for practical purposes, in the same sense as Arons (1997) is speaking of "inductive and deductive reasoning". These expressions have their more casual meanings, and the fact that they have been targets of logical analyses does not invalidate or render useless their original casual meanings. This point has been very cogently discussed by Toulmin (1958/2003), who in fact sees strict logic rather as a dead weight and burden than as an advantage.

and the interpretation of observations and experimental results, that is generation of meanings and conceptualisation, are generalising inductive operations. Inductive reasoning leads from specific empirical results to general theoretical conclusions or interpretations, hypotheses, concepts, formulations of laws as relations of the concepts, causal models and, ultimately, to theories.

Correspondingly, expectations and predictions based on theory are specifying deductive operations. Deductive reasoning leads from theory to predictions concerning specific entities and phenomena in specific circumstances. Testing the predictions requires new experiments which may support the hypotheses, falsify them or require their modification, thus definitising our knowledge of the validity of the concepts and laws. Complementary experimental results lead to further inductive reasoning. Concepts and conceptual structures are thereby developed further, which leads to new predictions and further loops in the cycle. This continuous cyclicity with an associated readiness to check and refine again and again one's conceptions on the basis of new empirical evidence is characteristic of science.[22]

In the schematic model discussed here, the scientific and the technological processes are driven by the same two-way dynamics of the interaction between Nature and the mind. They also share its hierarchical development into the methodical cycle. Naturally, the scientific and the technological procedures carry their own special characters due to the opposite directions of the processes and the different nature of their aims and products. Closer discussion of the technological process is beyond the scope of this article, however.

4.2 Permanence of the Intuitive Nature of the Process

The procedures that split the groping phase of gestalt formation into successive operational steps require conscious activities. This creates a picture of science as a conscious logical process proceeding by the alternation of induction and deduction. However, meaningful use of one's *procedural knowledge* and *skills* in the advancement of the scientific—or technological—process requires *procedural understanding*. Each step arises from its role in the creation of meanings. Every procedure is, thus, submitted to intuition. This is obvious for any *inductive* steps from specific experimental results to theoretical conclusions, which can never be based on compelling logical necessity.[23]

Identification of the basic gestalt is intuitive. The gestalt created is a reduction of innumerable observations to an idea or a mental picture of an ideal pure entity, phenomenon or property.[24] The gestalt is adopted as the definition and is named. Intuitively, the observations are interpreted as different occurrences of this conceptualised gestalt. In this way, perception and conceptualisation always involve intuitive modelling and idealisation. In discussing entities, phenomena and properties in terms of our concepts, we are, in fact, referring to these intuitive ideal models. The purity of a phenomenon presumes

[22] Nearly all researchers and thinkers who have paid attention to the process of knowledge generation and discovery of knowledge, recognise such a repeated cycle. Chang (2004), for example, describes a similar type of cycle, and Helmholtz's conception of the progress of conceptualisation also includes such cyclical development (Jurkowitz 2002). The idea of the methodical cycle has also been applied in descriptions of the learning and teaching of physics, in a form closely related to that introduced here (see the references given by Koponen and Mäntylä 2006).

[23] In mathematics, however, the so called complete induction is a logically binding method of generalising proof.

[24] Nevanlinna discusses this process of reduction and idealisation of observations as the basis of concept formation in several articles (see e.g. Nevanlinna 1950).

isolation and independence from everything else. Therefore, investigation of a phenomenon requires laboratory conditions, where this isolation can be realised to a sufficient accuracy. Thus, identification of a phenomenon means, at the same time, identification of any possible disturbing factors. To regard an investigation as one of a pure phenomenon is empirically justified if the empirical impurities can be reduced below any specified upper limit. The significance of this idea can be elucidated by introductory experiments in teaching mechanics.

1. The concept formation of mechanics can begin from the basic intuitive idea of interactions as the only possible cause of changes in the state of motion. This implies that free bodies (i.e. bodies without interactions) would be in uniform motion (relative to each other). This idea is known as the law of inertia. Testing requires free bodies. The absolute absence of all interactions is impossible, but on an intuitive basis, horizontal freedom can be approached by reducing frictional forces. This motivates the use of the air track or air table. However, the investigation of uniform motion may be even more instructive by considering just sliding bodies on a slippery surface. Reducing friction without limits in a thought experiment can convince one of the empirical justification for this experiment.
2. Rolling bodies on a hard surface offer another possibility for an empirically justified investigation, where uniform motion is easily realised, even with greater precision. However, when proceeding to investigate interactions by collisions of free bodies, the use of rolling bodies is not empirically justified. Elimination of horizontal external forces is impossible beyond the frictional impulses needed to restore the rolling condition in the collision.

Introducing quantities as representations of perceived properties requires a separate, intuitive basic idea for each property. Laws are intuitive idealisations; experimentally, correlations of measured values of related quantities are observable. Intuitively we interpret them as manifestations of dependencies representable in terms of mathematical relations between the fictitious exact values of the quantities. Our internal vision seeks accurate laws to explain the inaccurate results of the measurement. The internal vision considers the law a more genuine representative of reality than the measured values. It thus gives us intuitive justification for smoothing out errors of measurement; for interpolation to areas between the measured values, and for extrapolating beyond them to other values, and for generalising them to new systems and situations.

Deductive derivation of theoretical predictions is similarly submitted to intuition as is induction. Any specific prediction concerns some particular perceived occurrence of a phenomenon. As the first step, this occurrence must be fitted to the framework of the theory. It involves intuitive identification of the empirical meanings perceived in this particular case with those of the structure and the structural elements of the theory. If this succeeds, a mathematical problem, defined by the formal structure of the theory, remains. From the point of view of physics, this is self-evident, and a necessary piece of calculatory routine dictated by the compelling logics of mathematics.[25] However, even this calculation actually operates in terms of empirical meanings, which must be taken into account when

[25] This "miracle" of models fitting the reality has recently been discussed by several authors (cf. Morgan and Morrison 1999 and references therein), who have also recognised the sequential fitting between the models and experimental results. A discussion of such models appears in Koponen (2007) from the perspective of their use in teaching. Sensevy et al. (2008) is also a similarly oriented study.

running the calculation. Eventually, the empirical meanings also determine the possible interpretations of the results.

It is justified to suggest that in empirical science, logic is not a property of the process, but an aim of some of its procedures.[26] The groping phase of structural perception reflects the intuitive desire for a logical structure. A structural gestalt is experienced as ready when an intuitively satisfactory degree of consistency is achieved. This is also evident in the tedious perception process of formulating one's scientific results or ideas in, for instance, preparation of an article. The logic involved in the quested rational ways of presentation is the result of an intuitive process, but, in the article, the results are presented as if they had been achieved "logically".[27] This is a common "white lie" of science, which easily hides the basic intuitive nature of science. Many have recognised that there is a difference between how laboratory results are arrived at, and how this procedure is written up for publication in research journals.

4.3 Inseparability of Counterparts of the Cycle

Science and technology appear as a hierarchically expanded intuitive interaction of nature and mind. Their common origin is where learning begins (i.e. in the early formation of sensual perceptions[28]—or even beyond). The original inseparability of the roles of "nature" and "mind" is preserved in the inseparable intertwining of empiry and theory. From the starting points of this article, one can conclude that in physics, *everything is both experimental and theoretical at the same time*. A strong interaction dissolves the individual identity of the counterparts, replacing them with the new identity of their combination.[29] All concepts, terms, quantities, laws and theories are dual empiric-theoretical entities, although their "theoreticalness" grows with the progress of conceptual development. Moreover, neither purely experimental experiments nor purely theoretical theories exist; all empiry is theory-laden, and all theory is empiry-laden.[30] Intuition dynamically couples these two basic elements into a "living whole",[31] ties the scientific process to empirical

[26] Hadamard (1945) writes (p. 106) "Some mathematicians are 'intuitive' and others 'logical'", but later adds (p. 112) that "…every mental work and especially the work of discovery implies the cooperation of the unconscious … there is hardly any completely logical discovery. Some intervention of intuition … is necessary at least to initiate the logical work." In a letter to Hadamard (1945) (Appendix II), Einstein writes: "the desire to arrive finally at logically connected concepts is the emotional basis of this rather vague play with the above-mentioned elements …. this combinatory play seems to be the essential feature in productive thought—before there is any connection with logical construction…".

[27] Hadamard (1945) (footnote 7 of Ch. VII) writes: "… almost every mathematician would be a logician according to his own judgment", and gives an example of the hidden intuition (p. 113): "I should think this to be the case with Hermite, who certainly did not omit anything strictly essential in the results of his reflections, so that his methods were quite correct and rigorous, but without letting any trace remain of the way in which he had been led to them."

[28] Nevanlinna describes in detail the development of science, particularly of mathematics, from everyday sensual perception. This theme occurs repeatedly in his publications (see, e.g. Nevanlinna 1932, 1950).

[29] This is intended as a physical metaphor referring to the formation of new particles from their constituents.

[30] In the literature, the theory-ladenness of observations is often emphasised (Hanson 1958), whereas the empiry-ladenness of theory seems to be largely ignored.

[31] Interestingly, Duhem also describes theory as a "living organism", that is always open to further developments whose concepts are never final or complete, and which is always open to redefinitions and reorganisation (Duhem 1914/1954). In Duhem's case, this is closely related to his "underdetermination" principle, which means that no concepts or laws can be verified in isolation, thus leading to the conclusion that theories are always beyond final justification or verification.

meanings and gives rise to its one-way propagation from empiry to theory. This is the indelible trace of the one-way propagation from sensual-stimuli to gestalts and from observation to conceptual understanding.

What is stated here about the relation of empiry and theory holds similarly for science and technology: The separation of science and technology is also only apparent; *the interaction of science and technology is so strong that it dissolves their difference*. Similarly, all science is technology-laden, and all technology is science-laden; all concepts bear, in addition to their scientific meaning as identifiable aspects of nature, a technological meaning related to their practical significance.[32] Science plus technology is a process in which these two basic elements are dynamically bound together by intuition which imbues them with empirical meanings and which gives rise to the propagation of science from empiry to theory and the propagation of technology from ideas of the mind to technological products.

5 Features of the Conceptual Structure of Physics

We perceive "nature" in terms of two basic "ontological gestalts", *entities* and *phenomena*,[33] both of which possess *properties*. Correlations between the properties are perceived as *dependencies*, which are further interpreted as manifestations of some "mechanisms" responsible for the laws. This leads to mental *causal models*, experienced as a primary understanding of the phenomena.

5.1 Unification Development

Once perceived, the basic gestalts become elements for further perception, thus giving rise to a structural hierarchy of gestalts. The generation of conceptual hierarchies then becomes a general principle of developing understanding. Understanding by generalisation can be related to the Galilean principle of empiry: Science does not answer "why", since only "how" can be investigated empirically. In view of the idea of structural perception this statement can be softened: "How" opens the only possible path towards "why". This does not deny the eternal human inquiry, but gives it a direction to be followed. The scientific process places the statement into practice. When humankind asks about the essence of existence ("What is matter, light, electricity, gravity? etc."), physics guides it toward investigation of their observable properties and empirical laws. The progress of understanding then manifests itself as the perception of more and more general structural gestalts and their representation by more and more general concepts.

Physics offers no final explanations, but a hierarchical sequence of more and more general and profound explanations: Repeating the question "how?" in a more and more general form, we find answers, which more and more seem to explain "why". This gives rise to the *unification development* of our expanding picture of the physical world. As a

[32] Tala (2009) has recently provided a very thorough discussion from the point of view of techno-science, which advocates a similar inseparability of technology and science. Although Tala's starting point is somewhat different, the general picture parallels what is discussed here.

[33] The word "object" is avoided; rather, entities are regarded as subjects of nature. *Entities,* material bodies or particles and immaterial fields "exist" in some *position* or area *of space*, at some distance from other entities. *Phenomena* are events or processes, ways in which entities behave or anything that happens to them. They take place at some instant in time or over some time interval before, after or simultaneously with other phenomena.

result, nature is perceived in terms of a *structural hierarchy of entities* and a *generalisation hierarchy of phenomena.*

Entities are understood on the basis of their structural constituents and their interactions. Physics has revealed to us a hierarchical sequence of more and more elementary particles. Within each system, the internal interactions of the constituents are responsible for preserving their identity within the structure. They must therefore be stronger, by an order of magnitude, than their external interactions, which bind them together in the system; consequently, a corresponding sequence of stronger and stronger interactions results. These sequences offer us a chain of more and more profound levels of understanding of the structure of matter. Elementary-particle physicists even cherish a dream of an ultimate constituent which would offer the basis for a "Theory of Everything" (Ellis 1986).

Phenomena are understood when recognised as manifestations of more and more general basic phenomena. Initially, the perception of a phenomenon is based on the consistency of many observations. Single events are understood as different manifestations of one and the same phenomenon. Phenomena and their empirical laws are understood when, by investigating different phenomena, more general laws are detected, which leads to the interpretation of single phenomena as special cases of an umbrella phenomenon. Phenomena initially perceived as independent are recognised as different manifestations of more and more general phenomena.

Figure 2 presents schematically the consequent gradual unification development of the classical world picture.[34] It starts from the "pre-classical" set of independent phenomenal areas and proceeds through great unifying insights, which have bound the different phenomenal areas together step by step. It is these insights which are the great achievements of the scientific process.[35]

In modern physics, the unification of interactions is a central theme. Electromagnetic and weak interaction are understood as manifestations of the same electro-weak interaction. Within the standard model, the electro-weak and the strong-interaction are, more or less definitely, also understood to be unified; but gravitation still poses a problem, however. This view can be extended retroactively. Interactions are, in fact, responsible for all different phenomena of the various areas of classical physics, and the classical unification development can be interpreted as a unification of interactions. All classical interactions except gravitation turn out to be manifestations of electromagnetic interaction. The hierarchies of entities and phenomena are, thus, bound tightly together into one great pervading theme of the developing understanding of physics.

5.2 The Role of Quantification

Physics has the reputation of an exact science due to the quantitative concepts that make possible the theoretical treatment of problems with mathematical methods. The meanings of concepts, however, are born on the qualitative level of concepts. The sequences of gestalts—(1) *space, time, entities, phenomena*, and (2) *properties, dependences, causal*

[34] This scheme was designed for teaching purposes. While combining different areas of physics into a whole, it ties the contents of the courses to the historical development.

[35] The unification development introduced here is in many respects similar to William Whewell's conception of how science progresses through unification. According to Whewell (1847) the natural sciences show a unification development driven by the logic of induction typical of all natural sciences, but of physics in particular. Also in Whewell's model different branches are united through discoveries of common explanatory bases and common methodology. This model is often referred as Whewell's tributary river model.

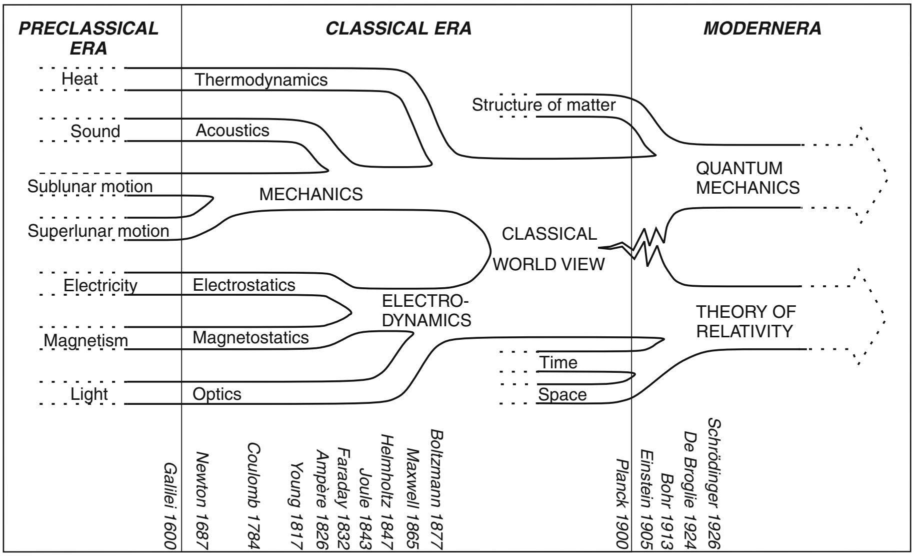

Fig. 2 Unification development of classical physics

models,—reflect the progress of structural perception in basic perception, which is the primary phase of concept formation in every phenomenal area. The quantitative level of concepts is built on the basis of this structure of the qualitative level by a process of *quantification.* In quantification, the qualitative concepts representing the second sequence of gestalts are transformed into *quantities*, *laws* and *theories* (Fig. 3). By this measure, the perceived meanings are transferred to the corresponding quantitative concepts. *Space, time, entities and phenomena* remain the "ontological carriers" of the meanings. Quantification creates no new meanings, but serves as *definitisation* of the understanding reached on the qualitative level. While transferring the perceived meanings to the quantities, quantification definitises the gestalts by joining in them the quantitative aspect of magnitudes. This

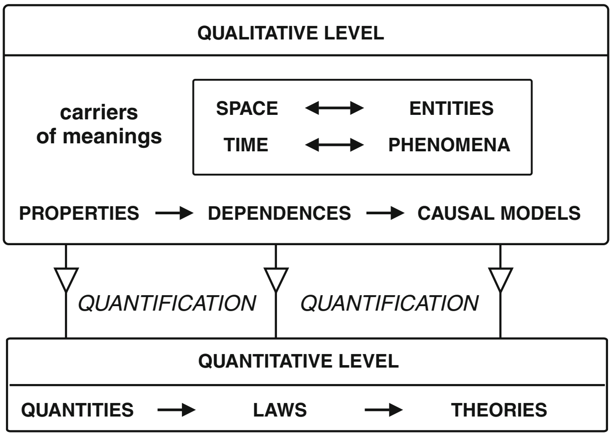

Fig. 3 Quantification and its relation to qualitative level

adds to the perception of the properties the sense of the "natural" orders of magnitude in different situations and circumstances, such as an idea of proper distances, sizes, ages or velocities.[36]

Thus, the conceptual structure of physics consists of two hierarchically different levels of concepts: the qualitative and the quantitative level, corresponding to each other. The quantitative level is a definitised representation of the qualitative one. Quantities, laws and theories represent a division of the quantitative concepts into three successive hierarchical levels. The hierarchical relations are clear: quantities are elements of laws, and laws are elements of theories.

"Theories" refer to the ordinary theories of physics and represent the highest level of structural hierarchy. A theory of a phenomenal area can be characterised as a general basic model of the phenomena of that area.[37] A theory consists of an idea of the nature of the entities in its coverage area and the basic laws governing the behaviour of the entities. This basic model offers the possibility of modeling; that is the formation of specific models corresponding to real phenomena and systems in different circumstances. In this way, theoretical *law predictions* concerning the phenomenon investigated become possible. Due to this *modeling capacity,* theory becomes the basis for understanding empirical laws.

In concept formation, the qualitative level precedes the quantitative level. This is also implied by the literal meaning of "quantification", which means *giving quantity to something previously regarded as having only quality*. The nature of quantities as *measurable properties* is expressed in international standards in slightly different formulations.[38]

The quantities are in a key position as the basic elements of laws and theories. Identification of the *properties* represented by the quantities and their linkage to entities and phenomena possessing the properties is a precondition of understanding the meanings of measurements, laws and theories. Quantification is implemented by quantifying properties into quantities and is a perceptional operation submitted to intuition (Sect. 4.2). Every property is a problem of its own. A corresponding quantity for each property must be created. In order for a property to be quantifiable, *different degrees* of it must be perceived. In fact, identification of a property already involves some perception of *"comparative Gestalts"*.[39] The basic perception phase therefore involves *pre-quantifying* observations of different degrees of (larger/smaller, stronger/weaker, etc.) or changes in (increasing/decreasing, strengthening/weakening, etc.) properties and verification of the way in which such differences or variations manifest themselves. While certain comparisons, such as longer, faster, warmer, or heavier seem obvious, many others, such as better, more beautiful, or more skilful, depend on subjective evaluation. To be quantifiable, the comparability of a property must—already on the qualitative level, fulfil the condition of *inter-subjectivity*.

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[36] That students propose senseless values for quantities as answers to problems is a common problem. One conventional problem in an entrance examination for studying physics at the University of Helsinki dealt with the shot put. The suggestions for the initial velocity asked varied from 3 mm/s to three times the velocity of sound. Obviously, the aspect of magnitude was not properly linked to the gestalt of velocity.

[37] This characterisation of theory as a collection of models is common in many views of the structure of science. In the semantic view of theories, for example, the theory is considered a collection of different levels of models, the highest level of which is called the theory (Giere 1988).

[38] ISO (1993): "Quantity is a property which can be identified as to its quality and measured as to its amount." ISO (2008): "A quantity is a property of a substance or a phenomenon that can be measured or calculated from other measured quantities." ISO (2009): "quantity: property of a phenomenon, body, or substance, where the property has a magnitude that can be expressed as a number and a reference." The earliest one of these is most explicitly related to perceptional concept formation.

[39] Niiniluoto (1984) speaks of "comparative concepts".

Pre-quantifying comparison of the degrees of a property leads inevitably to *quantifying questions*, both relative (how much larger? how much stronger? how much more beautiful? etc.) and absolute (how large? how strong? how beautiful? etc.). Nature should provide the answer. Appropriate formulation of the question requires a *quantifying idea* (i.e. an intuitively justified principle of quantitative comparison of the "strengths" or "magnitudes"). The idea, specific for each property, can be based, for instance, on the similarity or symmetry of entities or phenomena. This is taken intuitively as an implication of the equality of their properties and is often combined with the intuitive idea of additivity. After finding a principle of comparison and realizing it in a *quantifying experiment*, choosing *a unit entity or unit phenomenon* becomes possible. Comparison of the same property of another entity or phenomenon to that of the unit entity or phenomenon then yields its numerical value in the units chosen. This is the primary principle of measurement of the quantity, which completes the transformation of the quality into a quantity.[40]

Each quantifying experiment requires the measurement of some other quantities which must be known in advance. In this way, the meanings of all quantities are coupled to each other thus forming a *locally ordered net*. The development of any specific quantity can be traced in this net as a branching path which in many ways combines it to other quantities. The path begins from a node corresponding to the primary quantification, based on its empirical meaning as a property. At this node, the quantity is born as an invariant of an ideal entity or phenomenon presumed by the quantifying idea. It has a narrow validity, restricted to the reduced circumstances of the quantifying experiment. Each further node on the path is a generalisation, which extends the meaning of the quantity to new kinds of entities and phenomena. For instance, the meaning of "length" is generalised from the permanent length of an object to variable distances of entities, the length of a curved path, the radius of curvature, the lattice constant, the wavelength, etc. "Velocity", primarily that of a moving body, is imbued with the new meanings of phase velocity and group velocity of waves. "Temperature", originally a property of matter in thermal equilibrium, is extended to the temperature of radiation as well as, for example, to nuclear-spin temperature, where even negative temperatures have meaning.

In principle, each node is a new quantification based on the perception of an expanded empirical meaning. At the same time, the expanded meaning offers a new method for measuring the quantity and expands its range of possible values. It is essential that all these further nodes are bound by the preceding path to the primary quantification and, thus, to the perceived property on which the quantifying idea was based. The continuity of the path justifies calling it the same quantity throughout its entire growing area of validity; thus *the empirical core meaning of the quantity is thus preserved*.[41]

The local order of the net restricts the order in which it is possible to introduce quantities in perceptional teaching. It also evokes the obvious question of the "first quantity", the very origin of quantification. The answer is simple: The basis of all quantities is the "*number*", which is a quantity representing the magnitude of any given set of

[40] Quantification is in the core of so-called operationalism, introduced by Nobel prize-winning physicist Percy Williams Bridgman. "We evidently know what we mean by length if we can tell what the length of any and every object is, and for the physicist nothing more is required. To find the length of an object, we have to perform certain physical operations. The concept of length is therefore fixed when the operations by which length is measured are fixed: that is, the concept of length involves as much as and nothing more than the set of operations by which length is determined. In general, we mean by any concept nothing more than a set of operations; the concept is synonymous with the corresponding set of operations." (Bridgman 1927).

[41] This notion of empirical core meanings of quantities solves the problematic statement of operationalism that every experiment defines a different concept.

discrete entities or events. This quantity is based on the perception of entities and events as *individual* and *separate* and on the consequent *additivity of the magnitudes* of such sets. Natural numbers are its possible values, and the quantity "number" can, thus, be seen as the simultaneous origin of both quantitative physics and mathematics.[42] Weaving the net of quantities begins by quantifying of "time interval" and "length" in conventional "quantifying experiments", where "number" is required as the only preceding quantity.

5.3 Superposition of the Hierarchies

The two generative principles of hierarchy are joined together as two different "dimensions" of the development of understanding. Perceptional learning proceeds from lower levels to higher levels of conceptual hierarchy. The common practice of beginning with formulae violates this principle in relation to the quantification hierarchy, and beginning with electrons (e.g. in teaching electric current) violates it with respect to the generalisation hierarchy.[43] The coupling of the two dimensions of hierarchy is responsible for the development of the conceptual structure of physics.

Quantification serves as a driving force for developing conceptual unification in science. Quantitative investigations have played an essential role in creating the necessary foundations for progress through the generalisation hierarchy. Although quantification as such only transfers perceived meanings to quantitative concepts, it is a necessary precondition for the development of further structural empirical meanings. All phenomena of atomic, nuclear and particle physics stand on the "shoulders of a giant". Their production and identification—on the level of qualitative understanding—has become possible only through the whole preceding theoretical development of physics. The theories of classical physics belong to the perceptional foundation of modern physics. In contrast, the empirical evidence leading to modern theories forces us to change our understanding of the ontological nature of the initial basic gestalts.

The structure of the quantification hierarchy recurs in all phases of unification development. In contrast, unification development reflects back on all levels of the quantification hierarchy. It also manifests itself as the corresponding hierarchical development of quantities, laws and theories towards successive "*umbrella concepts*". Unification development drives a quantity forward on its "path" through the net of quantities. Extending the quantities from human-scale phenomena to the astronomical and cosmological scale (Hannula 2005) and even to the atomic and nuclear scale is an obvious example.

"Energy" offers an excellent example of such hierarchical development. Different kinds of energy, E_n, are quantitative representations of the primary empirical meanings of energy as perceived in different phenomenal domains. The unification is realised by quantifying experiments, such as the Joule experiment, which combine various kinds of energies in pairs to form more and more general "umbrella energies" until a final "unified energy" E covering all E_n is reached.

[42] The idea of quantitative measurements as the basis of theory formation was the dominant view of nineteenth century continental empiricism. For example, according to Johann Christian Poggendorf, one of the champions of German empiricism, the advantage lay with the theory that was then developed regarding "measure and number, the true foundation of exact scientific research" (Jungnickel and McCormmach 1986). This conception of physics became dominant in the latter half of nineteenth century continental physics, which aimed to produce through "measure and number" the foundations of physics.

[43] Bradley (1975) writes "… with good intentions, we have said to Robert: What matters is the atom, or the molecule or the equation. Poor Robert … resembles a child aged six given logarithms to multiply three by two …."

Fig. 4 Unification development of energy and mass

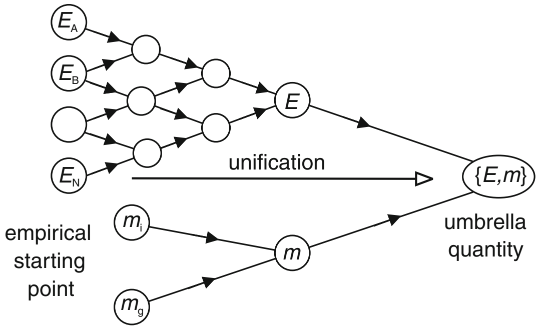

Figure 4 provides a rough oversimplification of this development. Its main defect is that it provides a misleading picture of the nature of the quantifying experiments, which are always unifications of two primary types of energy. Direct experiments on any "umbrella quantities" are impossible. Correspondingly, inertial mass m_i and gravitational mass m_g represent two different properties of a body. The Eötvös experiment is the quantifying experiment for the "umbrella mass" m. In principle, the quantifying empiry on which the mass-energy umbrella concept $\{E, m\}$ is based (i.e. the verification of Einstein's relation $E = c^2m$) consists of unifying these two primary mass concepts separately with each one of the primary "type-of-energy" concepts (i.e. verification of all possible relations $E_n = c^2m_i$, $E_n = c^2m_g$).

6 Projections on Learning and Teaching

6.1 Perceptional Teaching

Recognising *structural perception* as an important principle of learning enables one to conclude the general principles of the perceptional approach to physics.[44] The two mottos *"meanings first"* and "*ask nature"* crystallise two central ideas. New concepts are adopted only because they are necessary for representing their perceived empirical meanings. The *three-process structure* of perception and the nature of perception as a *one-way process* driven by *two-way dynamics* offer guidelines. A child possesses the beginnings of these processual elements. In perceptional learning, these scientific elements grow naturally. The task of perceptional teaching is to identify and to activate these elements, and thus to promote this development.

Identification of learning with science shares the significance of the history of science in teaching. History tells how the "correct gestalts" were once perceived, thus indicating how the perception can be reached anew. Paying attention to the roles of the three processes in the advancement of science may prove useful. The *equitable activation of all three processes* is necessary for learning, just as it is for progress in science. This is a question of the versatile and flexible use of proper teaching procedures. Identifying the relationship of the

[44] Arons (1997) presents a "list of processes" (Sec I: 13.2) in excellent agreement with the perceptional approach. In the terminology of this article these "processes" can be characterised as procedural instructions. Most of them derive naturally from the processual dynamics of the learning process as suggested by the "practical teaching philosophy" presented. For points of agreement with and differences from Arons' views the book review, Kurki-Suonio (1998) can be consulted.

procedures to the processes is therefore important. For instance, the "hands-on" doctrine of science teaching clearly emphasises the role of the technological process in developing conceptual understanding and group-working procedures encourage the social process, yet the inseparability of the three processes can be noted as an idea behind the Science–Technology–Society (STS) doctrine of curriculum development. Identifying pupils' initial levels and facilities is reduced to questions related to each of the individual processes. Experiences from teaching support the idea that pupils have "processual preferences". Their procedural facilities with respect to the different processes can be essentially different. Scientific—technological, theoretical—empirical and individual—social seem to be three largely independent dimensions of pupils' attitudes or learning facilities. Their positions with respect to these dimensions would be worth noting.

The possibility of guidance by a teacher as an element of the social process distinguishes learning from science. In science, the path forward must be found through "peer negotiation". Small scale "peer negotiation" among pupils is also a valid procedure in teaching and is necessary for developing pupils' abilities to speak of natural phenomena, describing their observations, and identifying and formulating their own ideas. Peer negotiation is also useful as a simulation of the procedures involved in scientific research. Negotiations often lead to incorrect conclusions, just as in the history of science. The teacher can point out such inconsistencies or neglected critical observations while in the history of science, obvious empirical features have sometimes long eluded attention, until someone pointed out the empirical facts that rectified the misconception.

In a complementary education course one of the participants reported a fine example of the motion of a parachutist, specifically, what happens when the parachute opens. The "peer negotiation" of the pupils led to the unanimous agreement of the whole class that the parachutist suddenly begins moving upwards. The teacher had great difficulty convincing the class of the empirical evidence, which was contrary to the pupils' evidence gathered from a TV programme.

The learning process should be guided in the direction of perception (i.e. from observation to understanding, or from empiry to theory) following systematically the *development of conceptual hierarchy*. The common classroom procedure of beginning from the theory, introducing quantities as algebraic expressions of other quantities and natural laws as equations, from which phenomena can be deduced as different manifestations of the theory, obscures the picture of physics as an empirical science. It conceals the meanings which are the key to understanding. Arons (1997) calls this "backwards science". On an advanced level, this so-called *axiomatic-deductive approach* may offer a shortcut to the comprehensive mastery of knowledge. Premature use of it, however, is *naïve theorism*: students are urged to jump directly to the highest hierarchical level of concepts, by-passing the basic phases of empirical concept formation where understanding originates. As a result, physics appears as a sub-field of mathematics, as an accurate structure of knowledge. Nature is only its annoyingly imprecise manifestation. Experiments are even harmful, since they will inevitably shake one's confidence in the accurate laws given.

Two-way dynamics are the driving force of one-way progress and a precondition of the "organic growth" of perceptual learning. Two-way dynamics should be permitted to develop from the child's own natural ways of reasoning[45] and guided towards the

[45] Mach (1866) writes "It is a prevalent but wrong opinion that children are not able to form precise concepts and come to the right conclusions. The child is often more sensible than the teacher. The child is very well able to comprehend, if one does not offer too much new at a time, but properly connects the new to the old."

methodical cycle. They should be guided towards the perception and conceptualisation of those gestalts, which were first perceived by the genii of the history of physics. In this process, they must have sufficient time for the groping phase, with proper supporting guidance by the teacher calling for further observations and appropriate variations of experiments, as well as considerations of the meanings of the results and consequences of the interpretations.

The empirical basis for natural laws can be elucidated through proper experimentation. However, experiments as such cannot provide a clear idea of the role of empiry. In the so-called *empirical-inductive approach,* the central role of intuition is easily overlooked. This leads to *naïve empiricism,* where demonstrations and pupils' experiments are considered "derivations" of natural laws. As a result, physics appears as an *induction automaton* accumulating theoretical knowledge by the obvious idealisations and simple generalisations of experimental results. On the other hand, a common response among the pupils to experiments in physics teaching is to complain, that phenomena investigated in the physics lessons have nothing to do with real phenomena occurring in Nature.

Children's own observations and experiences should be respected. Although space should be given for their own observations and interpretations, children cannot be expected to re-invent important ideas of science by themselves (Driver 1986). Children require guidance to comprehend the idea of a laboratory experiment, why careful design is necessary to formulate a specific "question for Nature". Conveying the idea of ideal "pure phenomena" as intuitive reductions of the natural phenomena is important, as the reduction to "pure phenomena" offers the only possibility for the investigation of natural laws that can be expected to explain the inseparable multitude of real phenomena. Thought experiments are necessary in finding ways to eliminate disturbing factors and to approach the ideal circumstances of pure phenomena. This helps to motivate one to conduct the experiment and to orient one's attention properly. All this is far more important than the laws themselves.

6.2 Procedural Understanding

Experimental and theoretical procedural knowledge and skills are tools for running the two-way dynamics. "Meanings first" also involves the learning of procedures. When studied at the pace of the progress in conceptual hierarchy, the procedures develop naturally. They are motivated by need. This is the key to procedural understanding: awareness of the roles of procedures in the creation of meanings and in conceptualisation. The roles of the procedures can be identified by linking them to phases 1–5 of the methodical cycle (Fig. 1). In this way, conceptual aims are attributed to the intended sequence of teaching actions, which are then joined together into a meaningful course.

For example, graphical representation is an important mathematical procedure that should be learnt early. It serves both representation (2) and prediction (4). Training of its uses in both roles is necessary, as is identification of the role for each application. The primary direction of the process suggests beginning with its use in representation. Construction of a graph (2) on the basis of data obtained in a simple controlled experiment (1), preferably one's own, is the natural first step. The problem of predicting interpolated, or extrapolated, values serves as motivation for the "smoothing out" needed in drawing the graph. This also leads to the explicit procedure of reading such values from the curve (3) as a prediction (4) for additional measurements (5). Subsequent variation of, say, the "strength" of the phenomenon in the experiment (1) and comparison of the resulting graphs helps one to perceive the relation of the "parameters" of the curve to the "strength", as an introduction to their representation by quantities characteristic of the phenomenon (2). It then becomes possible to deduce, in reverse, the nature of the graph corresponding to a given "strength" (3) as a prediction (4) for a subsequent test experiment (5).

This example also describes the use of the same experiment in either of the two different principal roles. An experimental operation, whether observation of a phenomenon, performance of a demonstration or experiment, or variation of an experiment, has—and should have—a conceptual aim, which defines its role. This aim can be either perceptional (1) (i.e. identification of gestalts as an introduction to conceptualisation) or a test (5) (i.e. investigation of the validity of expectations or predictions resulting from a preceding discussion or theoretical considerations). Identification of the role of action in the cycle, and its specific aim, whether a gestalt to be perceived or a test of a prediction, determines its position in the teaching sequence. This identification is necessary for both the pupil and the teacher. It forms an important element of teaching in student laboratories, where experimental procedures are learnt, as well as in problem classes, where the theoretical procedures are learnt. From the perspective of the perceptional approach, enhancing the facilities for designing experiments and problems for predefined roles and conceptual aims is essential in teacher education.

6.3 Ladders of Understanding

Figure 5 shows a breakdown scheme summarising the different aspects of concept formation for physics teacher education described in the introduction.

These seven items combine the two dimensions of hierarchy and the idea of the scientific and technological processes. Items 1–4 are the successive hierarchical levels of the quantification hierarchy. In perceptional teaching, their order is constrained and each level must be traversed for integrated understanding; omission of any of the lower levels leaves a hole for understanding to escape. (In the Finnish courses the scheme was called "ladders of understanding".) Item 5 brings in the technological process. It plays an important motivating role in instruction, but in this scheme does not represent an independent conceptual level. Item 5 occurs rather as an element of level 1, thus including aspects of items 2–4 also. Item 6 makes this process cyclic by returning repeatedly to items 1–5. Finally, items 6 and 7 together shows the subject as a part of the unifying development, and places it into the historical perspective.

In practical teacher education, this scheme has in many ways served as the basis for discussions and exercises. The first part, items 1–4, served as a tool for finding appropriate paths of progress for perceptional teaching. One of the exercises often used has been formulated as follows:

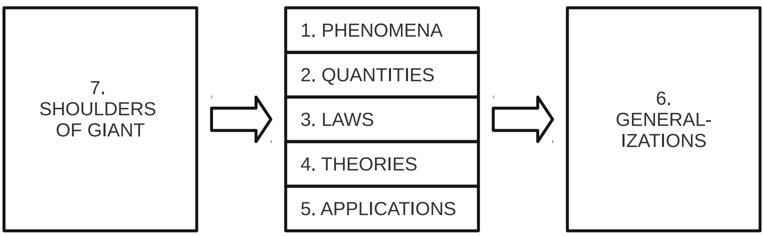

Fig. 5 The basic elements of understanding physics

Phenomenon—from concrete to abstract:
Analyse the conceptual representation of a given phenomenon.

- Identify its four-level hierarchical structure and the ways in which the higher levels rest on the lower ones.
- Consider the learning and teaching of the subject as a perception process proceeding consistently from the qualitative level of observations to the level of explanatory theoretical models.
- Note 1: Avoid "backwards steps", where lower-level concepts are justified on the basis of upper-level concepts. Do not begin with an explanation before you have anything to explain.
- Note 2: Remember: a phenomenon is what you observe, and not how it is explained.

The notes were added after the first teaching experiences of this exercise and reflect the main problems encountered during the exercises:

1. Discussing the phenomenon as an observable phenomenon, without reference to quantities and laws proved difficult.
2. A theoretical model was proposed as the phenomenon, representing a direct jump to level 4. For instance, the phenomenon of an electric current was understood as a flow of electrons.
3. Difficulties were encountered just in finding occurrences of the phenomenon in the environment.[46]
4. Students tended to formulate, as the starting point, a final exhaustive definition of the phenomenon in the most general way that present knowledge could possibly allow (a shortcut past the generalisation development). A parallel shortcut effect was encountered on level 2 of the quantities; students introduced "all possible" quantities related to the phenomenon, although, at the beginning, only those few quantities necessary for identification of the phenomenon would have been appropriate.

6.4 Basic Perception

Perception of the basic gestalts of entities, phenomena and their properties in relation to time and space and to each other represents the primary phase of understanding physics. This refers separately to each phenomenal area and indicates the importance of an initial *basic perception phase* in teaching any subject of physics. This would involve discussions of children's own experiences and observations, drawing attention to the gestalts characteristic of the subject area. From the point of view of different phenomenal areas of physics the teacher therefore needs the facility to discuss the everyday experiences of children of varied backgrounds, To guide the perception, the teachers themselves should be able to see not only that "physics occurs everywhere", but even that "all physics is present everywhere". For this purpose, special exercises were included in the programme for physics teacher education. Below are two examples:

[46] The phenomenon of "rotation" was discussed as follows: Where in our surroundings might rotation occur? Long silence—a shy suggestion: "merry-go-round"—another silence—"spinning top"—silence—pointing to the window: "Does the thing on top of that tower rotate?" The participants were advanced physics students. Diagnosis: all preceding studies of physics, in the school as well as in the university, had no connection to the real world of phenomena. To find empirical meanings, one had to return to one's memories of childhood.

1. Physics in the daily newspaper:
   - Select one news page from some daily newspaper. Examine the entire contents of the page and verify the connections of the occurring items to physics.
   - In a way you find appropriate, classify the contact points found on physical grounds on the one hand, and on the basis of the nature or degree of their connection to physics, on the other.
2. Physics in the environment:
   Analyse the physics observable in the context of the item or situation suggested[47]: Identify the phenomena of different sub-domains of physics.
   - What possibilities exist for the identification or verification of the basic gestalts, i.e. entities, phenomena, properties and their mutual dependences, on the different subfields of physics.
   - To what extent is it possible to perceive quantities and laws familiar from school physics?

The basic perception phase also has an important *linguistic aspect*. Nouns, verbs and adjectives, for instance, carry the meanings of entities, phenomena and properties, respectively, as a result of the conceptualisation of the basic gestalts. Through language, the structure of basic perception is socially shared.

It is important to learn to speak of one's observations as the first phase of conceptualisation. The meanings of concepts cannot be separated from their linguistic use. It is insufficient to define the concepts and to physically justify their adoption. The meanings are internalised gradually by practising their use in different contexts. *Models of proper linguistic use* of the concepts are therefore necessary.[48] The basic conceptual categories of *entities, phenomena, properties and quantities* each have their own characteristic linguistic usages, which reflect their nature. This aspect merited special attention throughout the course of physics teacher education. In addition, an exercise designed to aid in the identification of the conceptual categories was included:

Identification of conceptual categories:

> Consider the possibilities for positioning, according to their meanings, entries from a given extract of a text-book index into the following conceptual categories: entities, phenomena, quantities, laws, models.[49] At the same time, consider possible conceptual classes for those entries which remain unclassified.

Students realised that implicitly mixing conceptual categories is a common problem of linguistic practice in physics on all levels (Kurki-Suonio and Kurki-Suonio 1989).

[47] The situations suggested for analysis were drawn from children's everyday environment, such as "my morning from bed to departure for school", "garden", "sauna", "playground" or "a normal non-science classroom". One set was taken from titles of the primary school science curriculum and textbooks: "safely on my way to school", "animal species", "children and health", and "appropriate clothing".

[48] The linguistic use of terms reflects the ontological position of their referents and the modes of causal thinking, as Lakoff and Johnson (1980), for instance, have discussed at length. Taking care that terms are used in linguistically proper form helps students to form an appropriate understanding of the referents of the terms, while incorrect use may cause unnecessary problems.

[49] The suggested category of "models" was an intentional trap intended to help the participants to realise that, in fact, all concepts are models (*cf.* 4.2).

6.5 Meanings of Quantities

When students were asked the definitions of quantities in test inquiries or exams, the answers were regularly little more than mere collections of formulae. Questions about their empirical meanings evoked only confusion. Moreover, the linguistic practice of physicists—students, teachers, scientists, textbooks—is replete with incorrect and misleading linkages as well as "floating" or unlinked quantities that leave the meaning vague. Therefore, much effort was offered to recognise and handle this problem in teacher education.

The mechanics section of the course on *Conceptual Structures of School Physics* opened with a common discussion. The participants were asked to list *all the quantities of mechanics*, they could remember, and to *classify them into properties of bodies (or matter), motions and interactions.* In addition, an exercise on the subject was regularly included in the course on *Principles of Didactical Physics* as preparation for the detailed discussion of quantities on the lectures:

> *Meanings of quantities*:
>
> Consider the meanings for the given quantities *i.e.* state the corresponding perceivable property and identify the entities or phenomena which carry the property and the way in which the property is linked to them. (The question of how to identify the correct or appropriate "carriers" of a property—"weight" and "colour" as two problematic examples in school physics also arose.)

The question of the meaning of the quantities is one of the most central questions where many aspects of concept formation become embodied. On the other hand, this question is difficult to answer, because quantities have no final definition. In the exercises, students were guided to the answers in steps, discussing at each stage one of the following four questions:

1. *Linkage and characterisation:*
   - (a) To what entities and phenomena is the quantity linked and how?
   - (b) What kind of property is represented by the quantity?
2. *Experimental definition:*
   - (a) What is the empirical law which motivates the adoption of the quantity and enables one to choose its unit and to measure it?
   - (b) How is the quantity measured?
3. *Theoretical meaning:*
   - (a) What is the position of the quantity in the basic theories of physics?
   - (b) What kind of models does the theory employ to explain the defining law and to predict values of the quantity and changes of the quantity in different situations.
4. *Generalisation:*

   How does the area of use of the quantity expand and what is its ultimate coverage in entities and phenomena?

In fact, in characterising a quantity properly, all four of these questions must and can be answered. Another exercise was carried out on the meaning of laws with a corresponding set of guiding questions. In these exercises, nearly all aspects of concept formation—from the formation of the gestalts to the level of theory—are contextualised and concentrated in a single concept.

7 Reflections and Conclusions

The ideas discussed are the outgrowth of attempts to solve the basic problems of physics teaching and to unveil to students the general conceptual structure of physics and its empirical basis. The problems, due to the imbalance between empiry and theory in teaching (with the appearance of a Scylla and Charybdis of naïve theorism and naïve empiricism) seemed an endless tangle of problems in Finnish physics education in the late 1970s, and remains so today. Perhaps, such problems will remain unsolved, but one must be prepared to tackle them with new generations of learners over and over again. Nevertheless, the approach discussed here has provided us with, at least a partial breakdown of the problems involved and a better understanding of the direction in which to seek appropriate methods and practices. It has also yielded appropriate suggestions for solving these problems on different levels of studies.

The model presented in this work never actually existed as the planned and designed starting point of the teaching programme. Rather, the model was born and matured as a result of discussions in teachers' courses, and assumed the shape presented here only gradually through years of practice and experience—a process of *Praxis* as Marxists might have say. As such, the model remains far from having well-defined theoretical foundations. The ideas and schemes were born one by one over three decades of development. The order of development of the different ideas was very much opposite to the order of their presentation in this paper, although all new formulations strongly affected the formulation of the previous ideas. To begin with, the idea of empirical meanings served as the necessary starting point for understanding physics, and the awareness of significant problems arising in the teaching of physics all over the world seemed to call for radical changes of the traditional ways of teaching (*cf.* Arons 1997).

In teaching, we sought to create an atmosphere in which participants could be active co-workers in the process of development. Each of the successive courses held during that time were therefore different, presenting different phases of development. The basic problem setting was practical: How could the conceptual structure of different areas of school physics be introduced beginning with the perception of empirical meanings? At the same time, strengthening the self-esteem of physics teachers as teachers of a discipline which in public discussion was rated as the least important and most repulsive subject compared with mathematics, languages or biology was considered vital. The cultural significance of physics, its nature as a science, and its interactive relations to other fields of science and technology, were therefore constantly under discussion.

The relationship between science and technology was also an important subject from the beginning, but the three-process dynamic was not perceived until the early 1990s. The idea of defining the processes through their aims was considered simpler and more economical than the numerous attempts to define science and technology found in the literature. The processes were considered as the gestalts of three 'pure phenomena', which could be discussed separately in terms of their procedures and products. They provided a basis for discussing the life-long and history-long hierarchical development of science and learning. In addition, the idea of a three-process dynamic led to a variety of discussions, about the relationships of different teaching procedures and doctrines to the processes, historical development of the procedures, circumstances supporting or inhibiting the processes, possible processual preferences of the pupils and their identification, and ultimately, how all these aspects can be enlisted to support students' personal growth and to increase their understanding of science.

As to the ontology involved, the model is to be understood to be a initial starting point of physics teaching. Its basic elements cannot be understandably questioned before the empirical compulsion for this is encountered with the progress in learning physics. In fact, it is, more or less a valid ontology for classical physics, to the extent that it could serve as a definition of "classical". It need not be questioned until empirical evidence, which forces one to develop the basic ideas of quantum mechanics and relativity, creates the compulsion to revise both the ontology and epistemology. This processual dimension of the model was essential in the teacher education, but it could not be discussed in this context in any detail.

Finally, the question remains: How has all this benefited and contributed to better teaching? This question remains unexplored; the only evidence is the feedback from teachers. During the past 30 years, a great number of teachers and teacher students (about 650) have participated in these courses. Although evidence based on systematic research demonstrating the advantages of the approach is lacking, the continuous feedback from former students of the courses (and current teachers) has been nearly unequivocally positive. The advantages of the exercises introduced in Sect. 6 are remembered even after many years passed. Many former participants regularly attend the short courses on current topics of physics for teachers (arranged annually by Helsinki University Department of Physics). On these occasions, discussions very often evoke on memories and recollections of the courses. Such feedback has always shown great appreciation, and teachers expressed how much the ideas they learned in the course have helped them in their daily work as teachers; they say that what they have learned goes beyond theoretical ideas and views and has proved useful in practice—they have been encouraged to create a "practical teaching philosophy" as was intended.[50] Unfortunately, no research based evidence is available to support these claims, but this unequivocal feedback seems to show that the approach and the exercises designed on the basis of it have truly managed to capture something essential in conceptualisation and in the ways one can use this knowledge in practical teaching, which teachers appreciate in their daily work. Many physics teachers actively follow the perceptional approach in their own teaching. These casual remarks provide at least some indication of the effect and impact of this work done in the field of teacher education.

[50] R. Kurki-Suonio (1999) reports about a course on perceptional empiry held as a part of the first complementary education course for in-service physics teachers in 1996–1997 with 150 participants: "After the course the participants were asked to do a personal self-evaluation of their progress in different respects, for instance in the planning of empirical wholes and in planning of single experiments. This yielded a large amount of surprisingly positive feedback. In a number of self-evaluations it was told that the participants felt that,

– they were no more tied to the textbook as they had been,
– they have learned to analyse and organize there teaching and got rid of 'separate' experiments,
– they have got new ideas and courage to plan own experiments on the basis of the conceptual aims,
– they have learned a lot of new experiments suitable for school,
– they have learned to use the "old experiments" in a purposeful way,
– they have learned to use the equipment of their own schools in new ways and,
– their way of teaching chemistry and mathematics has also changed.

It was told that the complementary education program "had developed and widened the knowledge and understanding of physics enormously", "gave confidence in adopting new working methods" and "gave a completely new view on the teaching.""

The applications and uses of the ideas presented here are perhaps best documented in numerous (over 200) MSc theses completed in *didactical physics*.[51] Many of them (35) have used the perceptional approach as a planning principle for teaching solutions or the analyses of teaching procedures and textbook approaches, in designing teaching situations and for designing perceptional empiry (laboratory work, demonstrations, *etc.*) in physics teaching. Many MSc theses have served as a basis for practical teaching solutions as well as for teachers' own development of their practices: 43 MSc theses involved the design of a teaching period, 34 of which included a practical demonstration and, at least, a brief evaluation of the results. Altogether they cover levels from preschool through upper secondary school and vocational school, including, for instance, special and remedial teaching and a laboratory course for the visually disabled. Evidence from MSc, licentiate and a few doctoral theses, in which perceptional approach has served as a guide, support the conviction that the elements and ideas presented in this work have provided useful tools for practical teaching in school, designing courses for different levels, coupling teaching to history and analysing teaching procedures.

Acknowledgments Many people have encouraged and supported the development of these ideas and their applications. First of all, without the continual confidence and co-operation of my late wife, Riitta, nothing here would have been possible. The contributions of Professor Maija Ahtee, Dr Ari Hämäläinen, Professor Heimo Saarikko and Professor Jari Lavonen have had an essential role in the work reported here. Of course, I can never forget the encouragement of the students in my courses. Finally, I thank Drs Hayo Siemsen, Karl-Hayo Siemsen, Ismo Koponen and Kalle Juuti for their help and for their insistent persuasion to write the present study.

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[51] This term was adopted to indicate that these theses were written within the programme of physics teacher education of the Department of Physics, while the theses in "didactics of physics" are done in the Department of Education.

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