The Concept of Force in the Perceptional Approach[1]

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Abstract

Learning is interpreted as a perception process where meanings are created before concepts. The primary meanings of physical concepts are born in basic perception of the relevant class of phenomena resulting to a mental model of causal relationships of the Gestalts perceived. Subsequent quantification is the threshold process which transforms the properties and their relationships into quantities and laws. In this process quantities are generated as invariants.

The concept of force is based on a causal mental model consisting of bodies, motions and interactions. Quantification creates the force from the strength of interaction. It is concluded that study of one body motions only necessarily leaves the force without meaning, and that treatment of motion separately from dynamics deprives the kinematics its basic motivation.

The force as a momentary quantity is highly abstract. It results from a generalization process starting from the preceding concrete "macro concept" of impulse representing the strength of a collision, which is generated through a quantifying collision experiment together with the mass as the measure of inertia, the change of momentum as the measure of the change of motion, and the "macro forms" of Newton's third and second law. The force can then be introduced as a constant of motion under a uniform interaction.

The Perceptional Approach

The perceptional approach is not intended to be any system of rules to be followed in teaching. "Perceptionality" is rather an attribute which could be attached to a multitude of teachers' personal approaches. It includes certain general ideas about the natural learning, which should be taken into account whatever the approach. The ideas have been

[1] in H. Silfverberg and K. Seinelä (ed.) *Ainedidaktiikan teorian ja käytännön kohtaaminen.* Matematiikan ja luonnontieteiden opetuksen tutkimuspäivät 24.–25.9.1993. Reports from the Department of Teacher Education in Tampere. University of Tampere 1994. A18/1994, 321–334.

developed and discussed on a course held for physics teachers biannually since 1981 [1].

1. Unity of research and learning. Learning is an expanding process starting at the birth. *Perception* refers originally to the creation of sensations from sensory excitations, which is the elementary process from which all learning starts. Sensual perception, learning, studying, research and science are different stages of the same process: creation of knowledge. In this chain the consciousness and structure increase hierarchically, but the basic nature of the process remains. Science is a highly structured perception process, and in the sensual perception it is possible to see the seeds of all essential processual elements of science [2, 3, 4].

The two basic motifs of the empirical science, the *understanding* and the *usage*, giving rise to the *scientific* and the *technological* process, are both present right from the beginning. The formation of Gestalts from the excitations of senses is the start of *representation*, which is the primary scientific subprocess directed from Nature towards theory. The excitations and the resulting Gestalts have the roles of the experiment and the theory, respectively. The mental pictures thus formed are understood to represent real *entities* and *phenomena* and their *properties*. They give rise to expectations concerning the structure and behaviour of the surrounding world. Thus, the *interpretation*, which is the secondary scientific process directed from the theory towards the Nature and leads to *predictions*, is also there.

The entities, phenomena and properties as perceived by the child are never just organizing Gestalts. They are loaded with practical potential, something that he is taking into account and making use of. When the child, quite naturally and intuitively, adapts his behaviour accordingly and when he searches his possibilities and limits through trial and error, he is starting the development of the technological process consisting of the two opposite subprocesses, the *application* and the *invention.*

It is, thus, a deep misunderstanding to think that the pupil's view on physics would be somehow contradictory to that of science. If not equal they are at least parallel. The teacher can learn much about learning from an analysis of the processual elements included in the concept formation of the empirical science. And, *vice versa*, the research scientist could learn much about his profession from a study of the learning process.

2. One-way process, two-way dynamics. The perception proceeds in one direction, from the observation towards the mind. It creates Gestalts from sensory excitations, mental pictures from observations. It is based on an unconscious interaction of the observation and the mind, where separation of their mutual roles is not possible [2, 3, 4].

There are no "pure observations". Some structure and laws, the archetypes of the human mind, control the character of possible Gestalts. Particularly, we are bound to the necessity to organize our observations in space and time. We, thus, experience the world to consist of some *entities*, subjects of Nature, existing somewhere in space and time, having some *properties* and giving rise to *phenomena*, changes or invariances with respect to time, by "doing" something. We are bound to perceive continuity of existence and causality related to it.

On the other hand, the mental pictures can never be "purely mental" constructions. They are always subordinated to observation. Our picture about the external world is necessarily adapted to our experiences. But even the most abstract imagination has nothing else to work with than the perceptional or conceptual material rooted in observation through the learning process.

The *science* is similarly interaction of the experiment and the theory, where the experimental and the theoretical elements are inseparably interwoven. The mental model about Nature grows with the hierarchical development of the perception process into physical theories. It fills us with preconceptions about possible interpretations of our observations. Every experiment has its theory, the theory of the phenomenon, the theory of the instruments, the theory of the set-up *etc.*, which predefines the nature of possible interpretations of the results. We are genuinely hindered from observing features which contradict our preconceptions. On the other hand, every concept, quantity, law or theory has its empirical basis, which forms the core of its meaning. There are neither purely experimental experiments nor purely theoretical theories [5].

It is an inevitable conclusion that learning is not a logical but an *intuitive process.* The basic intuitive nature of the sensual perception remains in the expansion of the process even up to the highest hierarchical level of scientific research. Both learning and research are conducted and controlled by intuitive sensibleness not by logical necessity. The *naïve empirism*, where laws and theories are derived from successive correct experiments, is equally impossible as the *naïve theorism*, where phenomena are "derived" from basic theoretical laws given.

The conceptual structure of physics cannot be built by binding inference, neither by induction or deduction nor by both in alternation. The only correct way to recognition of Gestalts, to which one could be forced by logic, does no exist. It should be a relief for the teacher to realize that he need neither try to find it nor pretend that there is one.

3. The meanings are born first. The understanding arises from perception not from the concepts. Perception is creation of meanings. The Gestalts perceived create the need for concepts as their abstract representations.

Conceptualization of Gestalts leads to the terminology, the language, which becomes a tool for further perception of higher order Gestalts. In this way the concepts build up new material for the perception process. They lead the way to a hierarchy of Gestalts and concepts with increasing generality and abstraction.

This is the essence of understanding in empirical science. Interpretation is born from representation. *"How" is the only way to "why"*. Understanding proceeds through recognition of ever wider and more general structural Gestalts of natural phenomena and through their representation by ever more general – and, hence, more abstract – concepts [2, 3, 4]. There is no other understanding. When man asks about the essence, what is matter, light, electricity, magnetism, heat, gravity *etc.*, the physics guides one to study the observable character of the phenomena, their empirical laws and mutual connections, and leads thus to a *hierarchical chain of ever more general representations*. The structure of physical knowledge is based on unifying ideas, which are the great achievements of science.

All this is similarly true in learning. The understanding must come first. Quantities and laws introduced as formulas and equations are representations before there is anything to represent. The postulates are not starting points but crystallized results of a long and tedious perception process. They cannot be derived because science is not a logical process, but this is no excuse for not guiding the pupils through the process of perceiving their meanings first.

Starting mechanics by postulating Newton's laws is marriage without love. It is defended by the claim that the understanding – and love – will develop afterwards through sufficient application of the operational possibilities offered. Well, it seldom does!

4. Concepts as processes. Once the meaning, instead of the formal representation, is understood to be the essence of a concept, the nature of concepts as elements of scientific knowledge is seen in a new light. The concepts do not exist without their meanings. And the meanings cannot be separated from the process which creates them .

Thus, the concepts cannot be understood as building stones of a theoretical structure which has a mapping on the empirical structure of experimental results. There is only one structure of Gestalts. The observation and the mind, or the experiment and theory, are inseparably coupled within each structural entity. The science is not driven by separate experimental and theoretical processes, but it is one expanding process which has the nature of perception [2, 3].

Moreover, the concepts of different hierarchical levels are not end products but active elements of the scientific process. Thus, the structure of science is not that of a monument built piece by piece from new results. It is rather a *network of coupled processes,* which all take part in the continual development of the whole. It therefore has a closer resemblance to a living organism.

5. The Problem of Physics. Transition from qualitative to quantitative methods and concepts gives the perception process a new dimension, which is characteristic to physics. This makes the physics different from all other branches of science and the learning of physics different from any other learning [2, 3, 4].

The learning of physics includes, in addition to the "normal" conceptual development, a *quantification* process. It is the threshold process which transforms qualities into quantities. It builds a structure of quantitative concepts on the foundation of the qualitative system of Gestalts. *Quantities, laws and theories* are the quantitative parallels of properties, phenomena and their causal mental models – or of the Gestalts of conservation, change, dependence, cause and influence.

It is true, the idea of measurement has been introduced also on other fields. But nowhere else does it give rise to representation of properties in terms of a hierarchical net of quantities, which are combinations of units and numerical values, and to quantification of correlations into laws, which can be represented as equations between quantities.

The quantification is a crucial threshold also in the learning of physics. A long step of abstraction is required to proceed from qualitative to quantitative thinking. Many difficulties trace back to trials to hide it or to smooth it out instead of helping the pupils to take the step conciously and intentionally.

Quantities as processes

The *quantities* are the conceptual basis of whole physics. Quantitative representation is based on quantities. They span the bridge from the observations to the theoretical models. They tie together the empiricalness and the exactness of physics. Empirical information is expressed in terms of them. The theories are defined through basic relations between quantities. Therefore understanding of the meanings of quantities is the key problem of learning physics.

In a perceptional approach quantities are treated as Gestalts like any concepts. Adoption of a quantity is a perception process. It can never be made in one step. It starts from perception of the primary empirical meaning which must be quantified and submitted to a continual development coupled to the development of whole physics. Definition of a quantity by a formula thinking that "it is all there now", is the most fatal mistake of physics instruction, preventing everybody from understanding anything [6, 7, 8, 9].

In order to "define" a quantity it is necessary to go through the whole process which creates the meaning of the quantity. This can be analyzed in terms of stages or subprocesses related to the hierarchical levels of the conceptual structure of physics:

1. The basic perception. *The primary meaning* of a quantity is a Gestalt born before the quantity. It is born on the qualitative level in the basic perception of the relevant class of phenomena. It is first conceptualized as a property (quality) of some entities or phenomena.

The *prequantification* prepares the way for the quantification. *Comparative Gestalts* referring to degree or strength of the properties make it possible to speak about stronger and weaker properties, larger and smaller entities or faster and slower phenomena *etc.* It leads further to realization of correlations which create the idea of causal relationships. In this way the property gets a role in a mental model, which relates it causally to other entities and their properties. This role acts as a guide when finding a suitable quantifying experiment.

2. The quantification. Prequantification awakes the question: "how strong, how large, how fast". An answer requires development of a quantifying idea, invention of an idealized simple experimental situation which transforms the comparative Gestalts into quantitative comparison of different degrees of the property. Realization of the idea leads to the *quantifying experiment*, the narrow gate of quantification, where the quantity is created from the property (quality).

The experiment must offer the possibility of choosing a unit, either by taking some reproducible degree of the property as the unit or by coupling the unit to the units of quantities measured in the experiment. It must also yield a definite value for the quantity in the units chosen. It has therefore the nature of verification of an invariance, which is the basic *defining law* of the quantity. Quantities are born as invariants.

There seems to be two types of quantifying experiments. One is essentially comparison of the degrees of the property in two entities or phenomena, essentially measurement of the property of the one by the property of the other. Quantification of distance and time are basic examples. There are many others, like the heat capacity and the index of refraction of a material. Quantification of the inertia into the mass, as described later, follows this principle. The other type is based on measurement of the property with the help of some other quantities. The velocity and the acceleration are typical examples, as is also definition of the resistance through verification of Ohm's law as the quantifying experiment.

3. The structurization. *The theoretical meaning* of a quantity is born through *structurization*, the threshold process leading from the level of quantities and laws to the highest conceptual level of theories. It is expressed by the position of the quantity in the structure of the physical theories. It makes possible theoretical prediction of the values of the quantity in different situations.

4. The generalization. The primary definition gives the quantity a restricted meaning, valid in the ideal situation of the quantifying experiment. It is followed by a process of *generalization,* where the meaning is extended to wider classes of entities and phenomena. The process is returning spirally back to all of the previous stages.

The definition of a quantity is, thus, not one step from concrete to abstract but a continual process or a bunch of processes. The meaning of a quantity consists of a chain of meanings of hierarchically different levels based on each other. The necessity of continual generalization makes impossible any closed definitions of quantities and emphasizes their nature as processes.

The Force

In the light of the principles discussed, three conclusions can be made about the teaching of force:

1. The nonseparable trinity of the perceptional whole. In *mechanics* the basic perception should lead to identification of three basic Gestalts, the *bodies* as the entities, the *motions* of bodies and the *interactions* between bodies as the phenomena which have a causal relation. To build up a mental model on an empirical basis one should focus the interest in situations where there is one (main) interaction between two bodies.

It will not be too difficult to help the pupils to perceive the *inertia,* the *magnitude of the change of motion* and the *strength of interaction* as respective properties of the three basic components. They are also easily prequantifyable. Stronger interaction is needed to cause larger changes in the motions, and larger inertia of a body makes its motion more difficult to change. At the same time causality is built in the model. Discussion of the observations should be guided to the conclusions:

– Only interactions change the motion.

– All interactions are between two bodies and affect both similarly.

– A body is normally involved in many interactions and its behaviour is determined by their combined effect – particularly, the effects of the different interactions on it may balance.

The bodies, the motions and the interactions belong together. The approach, common in text books, where the problem of representing motions, or kinematics, is treated first separately from the interactions, breaks this "trinity". This deprives the kinematical concepts of their basic physical motivation and makes kinematics formal and artificial and, thus, a demotivating start of the physics studies. It is concluded that kinematics should not be taught separately from dynamics.

2. The empirical meaning. Creation of the empirical meaning is the basis of any understanding. The critical question to be asked is: *what property of what entity* calls for the force as its quantitative representation. The answer is: *the force represents the strength of interaction.* This attachment gives the force a meaning which can be quantified.

If an interaction is the "host entity" of the force, it is evident that any approach based on studies of one body motions will leave the force without meaning. Because interaction is excluded from the phenomena studied the force does not represent any property of anything in this context. The basic perception should build a mental picture, where the strength of interaction has a causal role on which a quantifying idea can be based. Therefore it is necessary that the basic phenomenon to start with must include one interaction of two bodies.

3. High abstraction of the momentary quantities. The concept of force, as it occurs in Newton's second law, as well as the law itself, are "micro concepts", related to infinitesimally small (momentary or local) elements of entities or phenomena. They have a high degree of abstraction corresponding to that of the differential calculus, as compared to "macro concepts" related to entities and phenomena of immediately observable size and duration. It is therefore unrealistic to think that the pupils can grasp such concepts if you at the same time believe that it will take several years before they will be capable of understanding derivatives *etc.*

The perceptional route from concrete to abstract can be laid out by following general remarks:

* One should start from macroscopic phenomena and properties and find for them a quantitative representation in terms of "macro quantities and laws".
* Next, instead of "differentiating" the phenomenon and the concepts, one should restrict the study to a simple ideal case, where the concepts to be introduced occur as invariances representing the whole phenomenon or entity.
* The final step of generalization to the micro concepts should be postponed until the pupils are ripe for the tremendous abstraction.

In the case of the force this leads to the following conclusions:

* The *impulse* as a measure of the strength of a collision has a concrete meaning and would be more readily understandable than the force.
* The force and Newton's second law should be introduced in the context of a *uniform interaction*, *i.e.* the ideal situation where force is a constant of motion.
* There is no hurry to make the generalization to the momentary force. One may though note that the idea can be made concrete through graphical representation, which to a large extent can replace the abstract algebraic differentiation.

A Possible Scenario

A possible scenario following the principles of a perceptional approach to the basic quantities of mechanics could be built of the following elements:

1. The free body. Realization of the interactions as the only cause of changes of motion gives rise to the idea of a *free body* with no interactions obeying the *law of inertia*. The existence of an ideal class of uniform motions is thus motivated and an idealized experiment can be planned to test the law $\Delta\boldsymbol{r} \sim \Delta t$. This defines the velocity of the free body as a constant of motion.

2. The mass. Once inertia is perceived as the ability of a body to resist changes of its motion, a collision of two free bodies A and B can be invented as a possible method to compare their inertias. The changes of their velocities have a common cause, the interaction. The body with the larger inertia will therefore obviously suffer a smaller change of velocity. This leads to a purposeful set of planned experiments to test the idea, which is confirmed by the astonishing invariance: the ratio of the velocity changes $|\Delta\boldsymbol{v}_A|/|\Delta\boldsymbol{v}_B|$ is independent of the nature and strength of the collision. A collision experiment can, thus, serve as a measurement of the *mass* of one body with the mass of the other [10].

3. The momentum. Once the interaction is perceived as a common cause of the changes of the velocities, it can be argued, that the magnitudes of the changes in the motions of the colliding bodies should be equal. After introduction of the mass as the measure of inertia it is readily stated that the *change of momentum* $\Delta\boldsymbol{p} = m\Delta\boldsymbol{v}$ becomes an obvious measure for the magnitude of the change of motion.

4. The Impulse. The causal relation, which is the basis of the mental model, implies that the magnitude of the consequence, the equal changes of the momenta, expresses the strength of the cause, the interaction. In this way the causal model becomes quantified into the macro forms of Newton's third and second laws:

– An interaction gives the bodies equal but opposite impulses $\boldsymbol{I}_A$ and $\boldsymbol{I}_B = -\boldsymbol{I}_A$.

– The change of momentum of a body shows the impulse obtained by it, $\Delta\boldsymbol{p} = \boldsymbol{I}$.

5. Force and acceleration as constants of motion. Already in the context of the prequantification, when classification of interactions according to different mechanisms is discussed, it will be necessary to discuss the limit, where one of the interacting bodies is very large. This limit is required when the necessary step to one body problems is made. It is also necessary before the idea of a *uniform interaction* can be found natural. This idea might be acceptable and understandable in cases like interaction between the Earth and a small body close to its surface. Once accepted, it will be understood as an interaction which changes the momentum $\boldsymbol{p}$ of a body by equal amounts in equal time intervals Δt. This gives rise to the expectation that, for instance, falling bodies and bodies on an inclined plane would obey the law $\Delta\boldsymbol{p} \sim \Delta t$ in ideal circumstances. Verification of the law makes the ratios $\Delta\boldsymbol{p}/\Delta t = \boldsymbol{F}$ and $\Delta\boldsymbol{v}/\Delta t = \boldsymbol{a}$ constants of motion, yielding the force as a natural measure of the strength of a uniform interaction and giving rise to the concept of uniform acceleration.

6. The Weight. Galilei's law of free fall now tells that the gravity of Earth exerts upon a body the force mg where m is the mass of the body and g the acceleration of free fall. It is concluded that weighing is a proper method for the measurement of mass. This is also the first *law of force* and offers the possibility to study other laws of forces by comparison.

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