Formula disease, or how to avoid understanding physics[1]

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Every physics teacher has the noble aim to teach understanding rather than facts. There is a vast number of pedagogical studies proving in unison that the result is the contrary, a diversity of misunderstandings. This may be partly due to the fact that misunderstanding is easy to verify. It is much easier to realize lack of understanding than to grade the degree of understanding. To be able to measure the understanding and to develop systematic methods to improve it one needs an operational definition for it. This means practical guide lines rather than abstract speculations about the philosophical nature of understanding.

Understanding is more than knowing. It indicates also the realization of the significance of knowledge. It relates the information to the method and structure of physics. Here the method is *more* fundamental since the totality of physical knowledge is dictated by the method by which it is created.

The method can be characterised by two very general attributes. Physics is empirical and exact. This means that ultimately all physical knowledge is based on observation or measurement but that it is presented in the concise mathematical form. This, of course, is more or less equivalent to saying that physics is both experimental and theoretical. The question of understanding physics thus refers back to the relation of empiry and exactness or that of experiment and theory.

It is most important to realize that it is both - and, not either - or. The structure of our universities is misleading. It gives the impression that theoretical and experimental physics are separable independent branches of science. Still, the whole motivation of theory comes from experiment and vice versa.

Experiments are done in order to find laws of the phenomena studied i.e. to build up theory, or in order to check theoretical predictions.

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[1] Nordisk forskersymposium "Fysik i skolen, problemer og perspektiver"
Rapport, Aarhus universitet, 1984, 82–86.

Theory is done only in order to describe, present or explain the phenomena or to predict them.

Theory and experiment form a cycle where each is both the source and the purpose of the other. Therefore it is neither the experiment nor the theory which is the essence of physics, but it is both of them together and the relation between them.

Understanding experiment is theory and understanding theory is experiment.

The formula disease is use of formulae without reference to their physical i.e. experimental meaning.

The trick disease is doing demonstrations or conducting experiments without reference to the concepts or laws i.e. to the theory which explains them.

The former, irrespective of the elegance of calculation, means teaching theory without understanding. The latter, irrespective of the skill and beauty of the experimental performance, is teaching phenomena without understanding.

Of these Scylla and Charybdis of physics teaching formula disease is far more common. It is met everywhere where physics is taught, in any country and on every level. We can easily detect its symptoms in our teaching. It is very difficult to avoid. And it is extremely infectious, as can be seen from the examination papers.

The main symptoms of formula disease are
1. undefined concepts,
2. groundless statements and
3. senseless results.

The first one is the essence of the disease. Use of symbols and equations without reference to their physical meaning means use of undefined concepts. Any conclusions based on operations with undefined concepts are necessarily groundless, and without grounds any numerical results look equally acceptable. The initial speed in a 16 m shot putting can be equally well 3 mm/s as 2000 m/s, as I have learned from the entrance examination papers of our department. And I am sure every teacher has an ample stock of comparable examples.

Such examples are, however, only on the surface of the problem. Having read through thousands of examination papers and hundreds of model answers, solutions or explanations prepared by the teachers I cannot avoid the conclusion that we do not only let the formula disease grow in peace but we may even educate the pupils systematically into it. I take two examples of most simple questions:

1. What is Ohm's law?
Answer: $U = IR$.

2. Drop a stone from the height of 10 m. At what speed does it hit the ground?
Answer: $mv^2/2 = mgh \;\Rightarrow\; v = \sqrt{2gh} = 14$ m/s .

Both present the most common type of "correct" answers. And both give just a set of marks without reference to their meaning or the reasons why they are written. There is no sign of understanding. <u>A letter is not a quantity and a set of marks is not a law</u>.

The aims of teaching must determine the principles of grading, if we wish to measure the degree to which the aims have been reached. As long as we grade these answers worth anything more than zero, we contradict the main aim, the understanding, and encourage the formula disease.

The facts that these are typical answers and that we are tempted to accept them prove for heavy tradition of formula disease in physics teaching. One would expect that on any field discussion in terms or' undefined concepts would be impossible and would die into its senselessness already before starting. In physics, however, undefined concepts are used to build formulae and equations, and one can do algebra with them. This makes sensible business in itself with its own laws of correct and false. We can find mental satisfaction from exercising them. This "something sensible" occupies our mind and prevents us from noting that there is no physics involved.

In grading it is also easy to verify the correctness of equations, calculations and results and count the errors. This is close to an absolute objective principle of grading, except, that it does not measure the understanding but memory and mathematical correctness. Moreover, it encourages the pupils to read equations by heart and effectively prevents them from developing better modes of learning.

The superficial by-heart learning of equations becomes obvious if the "stone is dropped "from the height of h = 10 m" or "from the height of s = 10 m". This old habit of giving symbols in problems has probably started from the friendly idea of helping the pupils – thus, admitting that they only learn by heart – and to "improve" the result of the examinations. The symbols act as signals and recover from the memories the necessary formulae. Most probably "h" leads to "$mgh = mv^2/2$" and "s" to "$s = gt^2/2$, $v = gt$". The correlation between the formulae and the symbols given indicates the degree of by-heart learning without understanding.

Breaking the tradition of formula disease of this kind is certainly very difficult. If the traditional answers are worth zero, how to define requirements which could make possible a unified objective grading. Here we can seek guidance from the structure of physical knowledge. As created by the cyclic interaction of experiment and theory it consists of hierarchical levels of increasing degrees of order. This yields a natural general organization scheme for treatment of almost any kind of physical subjects:

1. Phenomenon and system where the phenomenon occurs.

2. Quantities which are essential for the system, surroundings and the phenomenon, and their measurement.

3. Laws specific to the phenomenon.

4. Basic laws or theory explaining the phenomenon and its specific laws.

5. For all laws and theories the area of validity is essential and brings in the further question of possible more accurate laws and generalizations.

6. Use of the phenomenon and applications of its laws form the practical aspect of the subject.

For instance, in order to tell what Ohm's law is, it is essential to mention that
– it deals with a component of a DC circuit (1),
– it concerns the current I in the component and voltage U between its poles (2),
– it expresses the linear dependence $I \sim U$ in constant temperature (3),
– it is valid for all normal metallic conductors for not too large currents (5) and
– it enables us to define the resistance $R = U/I$ as a

constant characteristic of the component in any DC circuit.

All these points belong to the law and none of them can be omitted from an answer. One might get better answers by asking for the pupils' explanation of Ohm's law e.g. to a friend. I am, however, afraid that this indicates in principle acceptance of the wrong and dangerous idea that the set of marks "$U = RI$" is the law and that all else is just some additional explanations needed to teach what it means.

In a good answer one might expect to find additional notes of the applicability and generalizations of Ohm's law for AC and electronic circuits (5) and, depending on the level, some reference to its explanation on atomic level (4).

In our second example the system and phenomenon (1) are already given in the problem and also important quantities (2) are mentioned. Essential is now to know the laws (3 or 4), which make possible the required prediction, and enough of their area of validity (5) to be convinced of the justification of their use (or accuracy of the prediction). One could do with the simple specific law of free fall (3), but the solution given above would require, in addition, reference to the energy principle (4).

In practice there is the problem that when the pupils start physics they already have a tremendous routine in solving mathematical problems using mere formulae. Teaching experiences indicate that the transition, into physical presentation of the solutions can be achieved by repeated corrections of the answers. The first round of correction leads to an "explanation stage", where formulae are still given as the primary starting point but are completed with explanatory after thoughts. A second correction is needed to change the order into the physical one. It takes some time, but pretty soon they get used to this way of presentation. And gradually they learn the idea that <u>physical problem solving is based on laws which are known to be valid for the phenomenon</u> and not on formulae memorized by heart. In the difficult fight against the formula disease this is encouraging.