Competence and Understanding—A Personal Perspective

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Abstract The differences between competences and understanding are explored and their complementarity is emphasised. As part of this, special attention is given to the communication process in education and to understanding as an internal learning outcome; these are illustrated by reference to difficulties faced by physics students who have autism spectrum disorders. There is discussion of the competences that physics degree course should aim to develop in students with special attention being paid to some basic aspects of communication competence and to the development of personal qualities. Some work done by the EUPEN Network and by the HOPE project is described. The process of degree programme design is described and examples are given of work in (a) developing a package of modules for self-paced flexible learning of mechanics, (b) development of "guided discovery learning" in nuclear physics and (c) Socratic dialogue methods in tutorials. Brief speculations are made concerning some possible implications of applications of artificial intelligence to education. Finally the essence of thinking like a physicist is illustrated by some quotations.

1 Introduction

This contribution to the proceedings of the 2015 GIREP-EPEC conference is a summary of a presentation at the conference which gave a personal perspective on some aspects of physics education based on the author's practical experiences of physics education at a research intensive university. As such, it does not fit into the normal pattern of physics education research (PER) publications; for example it makes little reference to published work on PER. The author does not consider himself to be strongly engaged in PER but rather to be an experimental physics researcher who also has a strong commitment to physics education at all levels and

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has extensive experience of teaching physics and designing physics degree programmes at university and some experience of school-level teaching and of designing teaching materials and methods. This perspective is based mainly on personal experience of university teaching, including the design, organisation and management of degree programmes. Crucially, it is also based on many years of interaction with students of physics, engineering and mathematics. It is also based on many years of cooperation with colleagues in many European countries.

The reader should step back a bit and consider some basic issues in education. Some may seem obvious but they are important and their implications should be considered carefully. There is a focus in this paper on principles which have wide applicability in different contexts and it is hoped that this will be of some interest to physics education researchers and I am grateful to GIREP for inviting me to make this contribution. This paper has two specific purposes: (a) to help clarify the importance in physics university education of combining student understanding with student competences, and (b) to try to pass on the benefits that accrue from a great deal of experience of designing and implementing physics degree programmes including the use of different teaching methods.

The most important thing I should do at the start is to acknowledge the great debt I owe to the students I have been privileged to teach, particularly my tutorial students. My interactions with them have taught me a lot, not just about how young people learn physics but also about physics itself—the questions they have asked me and also their responses to my questions to them have made me think more deeply about physics concepts, techniques and applications. The views and advice presented here are also based on many fruitful discussions I have had over many years with colleagues at Imperial College London and also with colleagues in the Institute of Physics in the UK and within the EUPEN Network of European physics departments. Although my understanding of educational issues has gained most from physics colleagues, I have also gained from discussions with mathematicians, computer scientists, neuroscientists and school teachers.

2 Communicating and Thinking

The essence of good teaching is good communication which is itself perhaps the most important "Key Competences"—the theme of this conference. Good communication depends on receiving as well as on transmitting. It depends on listening, reading, looking and then, crucially, on THINKING. This is the essence of education. Thinking must then be followed by a response. This can be an internal response but more effectively should be creative writing or speech. It is important that the input, the thinking and the response are remembered. I have gently introduced here an analogy to the first basic concept in Computer Science: The elementary Flow Chart INPUT → CPU → OUTPUT plus links to memory. This analogy is revealing. Figure 1 attempts to illustrate these processes. This is given a heading "Communication Flow Chart—Odin's Ravens". Norse legends tell of the

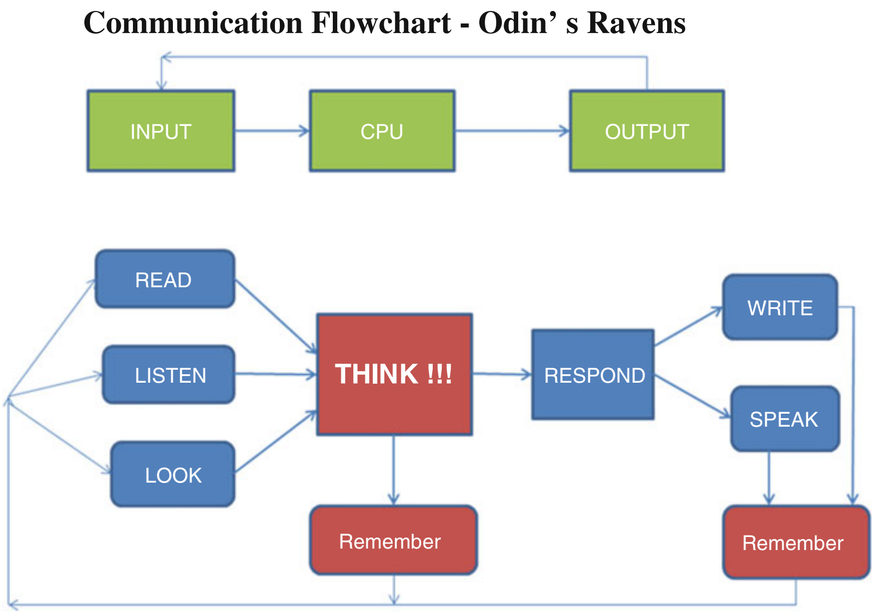

Fig. 1 Communication as a process of Input (Read, Listen, Look) leading to Thinking which in turn leads to a Response followed by Remembering and feedback. "Odin's Ravens" in Norse mythology refer to the key processes of thinking and remembering. The analogy with the basic flow chart of an introduction to Computer Science is shown at the top in green (where the feedback loop is optional). For laboratory based education, a "DO" box should be added before the "THINK" box

two ravens, Huginn and Muginn, that perched on the shoulders of Odin, the king of the Gods. Huginn helped Odin to think and Muginn helped him to remember—just how they did this depends on which account you read. The feedback loop is needed if the process is to result in two-way communication. It is crucial for some educational methodologies, e.g. Socratic dialogues.

All the above may seem like an excessive analysis of the obvious! But physics is often concerned with thinking deeply about apparently simple but fundamental concepts and an examination of the nature of communication is very relevant to education since good teachers listen to their students and think about what they say. Not everyone engaged in learning, teaching and communicating operates in accordance with this flow chart in a good way. Those who do are the ones who excel. Those who don't are a source of frustration for the teacher (or the student, for often it is the teacher who does not listen!). Of course, the quality of thinking is the key. This doesn't just apply to education. "Listen and think" is better advice than "do this".

Another reason for thinking about the flow diagram for communication and education is that it helps in adapting educational methods to cases where some individual students have difficulties (which we may refer to as disabilities) in understanding certain types of inputs or in producing outputs in a conventional form or indeed in the notion of feedback. These difficulties are often accompanied by an enhanced thinking ability and an internalisation of the process of learning. For example, some students with autism spectrum disorders (e.g. Asperger's syndrome) often have enhanced thinking ability (often unusually precise but lacking reference to context) which shows in high ability in mathematics and mathematical physics although their poor communication and social competence is a problem for both them and their teachers and so they are often regarded as foolish or as an enigma. Such students need special help in developing communication skills and in thinking about context. That can be very hard for them (and their teachers) although their internal understanding may be very good. In 1967, Lennon and McCartney wrote the song "The Fool on the Hill",[1] which epitomizes how the inner world of understanding may not be perceived by others if the thinker has profound communication problems. A physicist reading the lyrics of this song will be struck by the poetic way it portrays how "The Fool on the Hill" goes beyond immediate appearances by thinking deeply about what he sees and is then thought a fool by others because he cannot answer their questions. This illustrates the formidable difficulties that confront autism spectrum disorder students in attempting to interact with teachers.

3 The Concept of Competence

The main key-word of this conference is "Competence" used to signify both an approach to physics education, as in "competence based education", and also the competence of teachers and graduates. But what do we mean by the word "competence"? It can be defined as the ability to do something based on understanding—this combines the two essential qualities of "ability to do something" and "understanding". Thus, competence is more cognitive than a skill. This is widely acknowledged even though the meaning of the word "understanding" is debated. However there are different definitions of the word "competence", e.g. in the Tuning Project.[2]

"Understanding" and the "doing" implicit in competence are complimentary and reinforce each other although these qualities are sometimes seen to be in opposition to each other in the sense that concentration on acquiring competences can be seen as a diversion from understanding. Thus, to be referred to as "competent" can be interpreted as not being a creative or deep thinker. A characteristic driving force of physicists, both young and old, is to understand the physical universe on all scales,

[1]"The Fool on the Hill", Music and Lyrics written by Lennon and McCartney, first recorded Abbey Road Studios, London, 1967. The interpretation given here is due to the present author.

[2]The Tuning Project (Europe) is described in a very large number of papers which can be found at http://tuning.unideusto.org/tuningeu.

i.e. it is an intellectual pursuit. The result of this can be thought of as an internal learning or research outcome, whereas competence is essentially about having the capacity to affect the external world by doing something useful. This can include both communicating understanding and also applying your understanding to solving problems or advancing technology. These competences are particularly valued by employers of physics graduates and constitute one of the most important goals of physics higher education.

The difference between internal and external is also relevant to the psychology of learning and to the assessment of learning. To be assessed, understanding has to be demonstrated—the ability to demonstrate it is a competence but understanding itself is not. The internal-external difference is also relevant to students' medical and psychological conditions (e.g. autism spectrum disorders, sensory and motor problems, personality types).

4 Key Competences for Physics Graduates

There have been many attempts (e.g. the physics special interest group of the Tuning Project) (see footnote 2) to specify the competences that physics graduates should possess. They result in the production of lists such as:

- Ability to analyse phenomena in terms of physics knowledge, principles and mathematical reasoning.
- Ability to pursue a scientific investigation using experimental methods.
- Problem solving ability.
- Ability to apply knowledge to real world problems.
- Ability to work in teams including, interdisciplinary teams.
- Ability to communicate based on the writing of reports, giving presentations and giving general oral explanations to a wide range of audiences both specialist and non-specialist.
- Ability to use information technology, including computer coding, to pursue investigations and to solve problems.

More recently some other competences have been emphasized, such as:

- Ability to make mathematical models and computer simulations of physical processes.
- Ability to show creativity in creating and applying knowledge.
- Ability to innovate and to become an entrepreneur.

All of the above need to be explained and expanded in terms of what they involve. Moreover, they can be expressed using different words. It might help to describe key competences in terms of the basic requirements which they imply. Thus, the key competence of communication ability can be "unpacked" and expressed as guidance for students in terms of:

General principles of the key competence of communication ability:

- Think about your AIMS: *What are you trying to achieve by communicating?*
- Think about your Audience: *Make your communication appropriate for them.*
- Be a good listener and reader: *Do not always be in 'transmit mode'; respond, do not ignore.*
- Acknowledge contributions of others: *Avoid plagiarism.*
- Seek FEEDBACK: *Use it to improve.*

For Report Writing:

- Value clarity: *Write in simple direct sentences. Be precise.*
- Review what you have written: *Be self-critical and make corrections.*
- Take responsibility: *Always put your name and the date on what you produce. Feel responsible.*

Besides developing the above competences, education is also about developing personal qualities. These are crucial for both academic and career development and are also often the basis for decisions on job offers made by potential employers. They are sometimes classed as competences themselves. Through interactions with their students, universities have a duty to help them to develop these personal qualities.

- Ability to think rationally and carefully.
- Ability to learn from others and by one's own efforts and from one's own mistakes.
- Adaptability to new situations and new technology.
- Demonstrating empathy and a cooperative approach.
- Ability to convince others of your ideas and your results
- A willingness to take responsibility for what you do and write.
- To acknowledge the contributions and help of others.
- To guide and support others.
- To practice scientific and personal integrity.
- To have self-confidence when appropriate but also to be self-critical.

5 The Tuning Project and the EUPEN Network

The Tuning Project (see footnote 2) is a major initiative to reform higher education based on a competence approach. It has been funded by the European Commission. It started as a European project in the year 2000 but later became world-wide. It is too large and inclusive to describe here but its emphasis on competences gives it extra economic relevance. It has undertaken major investigations and consultations on competences in a wide range of academic subjects including physics. These have been more detailed and differentiated by type than those presented here. The definition of "competence" used in Tuning is somewhat different to the definition adopted in this paper although there is much in common in the ways of thinking about these issues.

The physics team in Tuning was drawn mainly from the EUPEN[3] network of university physics departments which has an even longer history of investigations into higher education in physics in Europe. This also has been partly funded by the European Commission in a series of specific time-limited projects. Some of these have made extensive investigations on differences in approach to physics education in different European countries. As an example, one provocative conclusion some years ago was "Physics is universal but physics education is not".

The most recent EUPEN project, called HOPE,[4] is underway at the moment. One theme in HOPE is an investigation into the factors that have inspired first year university physics students to study physics. A preliminary conclusion from this is that internal factors dominate over external factors. We see again the importance of the internal world of students. Thus, a wish to understand the world around us, the universe and how things work are the most important driving factors and a wish to learn advanced physics is seen as the key to opening these doors. The least important factors are the influence of friends and family members, visits from university staff, a wish to be a teacher, etc. But the investigation is not yet complete.

6 A Few General Principles of Degree Programme Design

(a) Know your students and make the programme appropriate for them.
(b) Think carefully about (and get agreement on!) purposes and then on aims and objectives.
(c) Design content and methods of teaching/learning to achieve these.
(d) Consider the interests and competences of the academic staff who will deliver the programme.
(e) Think of the students' needs as well as the point of view of the academic staff.
(f) When specifying desired learning outcomes, consider how they can be assessed.
(g) Think about how opportunities for creativity can be provided and motivation increased.

[3]EUPEN (European Physics Education Network) has published a series of books based on the various specific projects it has engaged in. These have mostly been Thematic Network Projects funded in part by the European Commission in various programmes of the ERASMUS, Socrates, and Life-Long Learning Programmes. An example is "Inquiries into European Higher Education in Physics: Volume 7". Universiteit Gent, 2003. ISBN 90-804859-6-9.

[4]HOPE (Horizons in Physics Education) is a project of the EUPEN Network, partly funded by the European Commission in the ERASMUS section of the Life-long Learning Programme (project number Nr 2013-3710_540130-LLP-1-2013-1-FR-ERASMUS-ENW), It is described in http://www.hopenetwork.eu.

(h) Consider how quality can be assured and enhanced.

A basic design principle is to think of things from the students' point of view and to allow them choice. Thus students should be stimulated and stretched intellectually but not overloaded with excessive detail. Opportunities for creativity should be built-in. We should remember that learning is a process of change. It is a change in the students' knowledge and abilities. This means that (at least in physics and mathematics) the change is a change in the brain (or more generally in the nervous system). If physics education is to be universal (like physics itself) then it should be based on cognitive neuro-science. But we cannot expect too much help as yet from this discipline since this branch of science is still struggling with basic questions such as the physical mechanisms of memory and of reasoning. But the relevance of cognitive neuro-science for educational policy is already starting to be recognised.[5]

Students differ, not just in previous education and experiences but also in terms of basic cognitive abilities and ways of thinking. Examples of genius and precociousness in different highly cognitive fields such as mathematics, art, music, chess etc. strongly suggest that these are, at least partly, consequence of differences (perhaps subtle and unknowable) in the neurological structure, connectivity and processes of the brain. The relevance of this for degree programme design is that opportunities for students to excel and to surge ahead must be built-in, just as opportunities for different specialities in the programme should be provided, and that allowance must also be made for students to use different learning methods.

Content is obviously crucial to achieving educational goals and the links, both educationally and logically, between different topics should be part of the design. As well as covering a common core, there should be a range of special topics to be chosen by students.

Teaching and learning methods are aspects of design. A great deal of experience has accumulated on various methods but a key aspect of all is the importance of interactivity between students and teachers. Conventional lecturing, when done well and involving interaction with students, has the advantage of enabling students to get good explanations of difficult topics and to question them. So questions from students should be encouraged and enabled even if this means that less ground is covered.

[5]Presentation of Prof. Sara-Jayne Blakemore, University College London Institute for Cognitive Neuroscience, at the meeting of SCORE at The Royal Society, London, on 24 Feb 2014. http://www.score-education.org/media/15383/final%20annual%20conference%20report%20-%20for%20website.pdf.

7 Improved Teaching/Learning Methods

In recent decades, improved teaching and learning methods have proliferated in response to evidence that conventional university teaching via lectures is not very effective in helping some physics students to understand physics concepts and that methods which generate increased student involvement and active learning are more effective. They also have been stimulated in response to advances in technology and particularly much enhanced capabilities and interactivity of computer based systems. The important point is that they should be embedded in the overall programme design.

There is a long list of teaching/learning methodologies which are used in physics, each with their adherents and each offering particular advantages:

Blended Learning
Flipped Learning
Inquiry Based Learning
Self-paced Learning
Peer Instruction
Flexible Learning
Guided Discovery Learning
Socratic Dialogues
Project Based Learning
Team Based Learning
Etc. …

All are well motivated and in most cases PER has provided evidence of their effectiveness which varies depending on circumstances and targets. However, their impact on university physics teaching has been disappointing. This has often been because there has been resistance from teachers who feel uneasy in adopting them because of a lack of time to learn how to implement a new approach to teaching. Also there is sometimes a feeling that some methods are not appropriate to their particular needs (in terms of student profiles and learning needs) and in particular are only suitable for more basic parts of the curriculum. They are also often difficult to incorporate in the overall teaching/learning design programme. Since they represent somewhat of a revolution, the famous (but unverified) last words of Simon Bolivar come to mind: "*Those who have served the revolution have ploughed the sea!*"

Two different non-traditional methodologies for physics teaching will now be described to illustrate both their motivation and the reasons why they actually made less impact than hoped for. They were carried out by the author and his colleagues at Imperial College London. Also a brief account will be given of the use of traditional Socratic Dialogues in physics tutorials. They are included here because they illustrate some of the above issues and in particular the problems in having new approaches embedded in overall physics degree programmes.

Development of Self-paced Flexible Learning in Mechanics for physics and engineering students
Problem: The reduced but variable mathematical content of school physics caused some physics and engineering students to struggle with classical mechanics in their 1st Year at university.
Proposed Solution: A special supplementary, flexible and self-paced course on Mechanics for Physics and Engineering students.
Method: An interdisciplinary team was formed to design and trial such a course. There was much discussion and much listening to advice from external experts and from students. This resulted, after a lot of work, with the production of a set of about 20 interlinked self-study modules on classical mechanics each consisting of (a) context, (b) pre-test, (c) formative tests, (d) end-of-module competence test.
Trial with students: About 30 selected 1st year students from physics and engineering took part in a trial of 3 of the modules: Particle kinematics, Free-body diagrams, and Newton's Laws. Students worked on the modules individually in a collectively supervised but self-paced manner on different days spread over about two weeks. There were in addition three separate short lectures on cross-module novel applications designed mainly to improve motivation and provide extra interest.
Measurements made and recorded: The times taken for each student to complete each module (completion defined by scoring a high mark in the final competence test) were recorded and also the marks in the formative and end-of-module tests were recorded. The tests were structured to measure achievement of a series of specific learning outcomes.
Results: There was a significant spread in the times needed to complete a module. There was found to be an anti-correlation between time taken and marks (which could be regarded as a proxy measure of the number of learning outcomes achieved), i.e. students who worked more hours achieved lower final marks and hence achieved fewer learning outcomes. This anti-correlation was significant at the probability level for each module of 2×10^{-5}. This confidence level was calculated using the Fisher Z transformation from the correlation coefficient probability density function to a Gaussian.[6]
Discussion of Implications: Students reported their understanding was improved but that the time taken was greater than conventional learning by lectures, books and examples classes. Academic staff who produced the modules reported that the staff time taken to produce the modules was excessive—about 5 × the time for a conventional lecture course including course work and assessments. The academic level reached was lower although basic competence was higher.
Conclusions: Full implementation was not justified although some parts were used as a "Mastery Course" in some engineering departments. The modules were tested using paper-based materials (this was several years ago) although interactive

[6]Course Design for Resource Based Learning: Technology (Case Study 6), Editors F. Percival and G. Gibbs. The Oxford Centre of Staff Development, 1994. ISBN 1-873576-25-0.

computer based modules were planned but not implemented because the considerable extra staff time involved was felt to be not justified. The anti-correlation between time taken (student work-load) and learning outcomes challenges the normal assumption that student progress is proportional to student work-load! All the students involved had satisfied very high entrance standards in maths and physics so it surprising to find this anti-correlation although it suggests that their ways of thinking are different. Although this investigation was done several years ago it is interesting that the basic methodology of flexible, self-paced learning with motivational episodes is similar to the methodology employed in MOOCs.

Trial of "Guided Discovery Learning"

This was a supplement to a 2nd Year lecture course on Nuclear Physics. It used *partly* developed computer programmes which students had to extend to investigate several different topics including (a) numerical solutions of the 3-D Schrodinger equation for modified Yukawa potentials to investigate predicted deuteron properties arising from different forms of the inter-nucleon force, (b) consequences of the Semi-Empirical Mass Formula, e.g. energetics of radioactive decays, and (c) dynamics of radioactive decay chains including branching. Students worked on adding their own code and modifying the programmes in ways that required creativity to investigate specific questions.

In principle this was very effective because of the partly developed nature of the computer programmes for students to extend; it was crucial that it followed a specific course on computer coding. It was limited by demands on computer resources (this was quite some years ago) and particularly by the problem of embedding it in the whole course. Assessment of student performance was also problematic.

Experience of Socratic Method in Tutorials (based on the author's experience of this at Imperial College London)

Small group tutorials were devoted to (a) discussion of student questions in the group (4 students plus tutor), (b) giving students interactive oral feedback on their written work, (c) asking students questions—making them THINK and discussing their responses with them (this is the essential Socratic Method), and (d) helping students to solve problems in real time at the whiteboard.

Students vary in their response but a good tutor will get each individual student to think and particularly to get students to explain their attempts to solve a problem. The crucial advantage comes from the interaction between tutor and students concerning questions from the tutor to the student. Moreover, students really gain from the opportunity to have discussions with experienced physicists and with other students.

8 Possibilities for Application of Artificial Intelligence (AI) in University Physics Education

The author makes no claims of any special knowledge of AI so the following cannot be regarded as authoritative but is intended to draw attention to the nature and possible impact of AI on education. Many educators have speculated that the relevance of AI to education could be profound in the coming decades. The main applications presently envisaged are in distance learning particularly in the context of MOOCs since AI should cope well with different students having different needs. Already starting to be used are methodologies based on adaptive algorithms (exercises, quizzing, feedback), sentiment analysis and machine assessment with individually tailored response to students.

AI raises some fundamental questions about education. Authoritative scientific knowledge is already easily available from the internet to use in self-learning; the problem is to distinguish it from the non-authoritative and also to develop thinking and problem-solving. So university education which is mainly about acquisition of advanced knowledge is questioned. The emphasis should be more on developing understanding and competence. But if AI really becomes pervasive it will call for fresh thinking on the questions of "Who needs to learn physics at university level?", "Who wants to learn and why?" and "Why go to university to study physics?" These are existential questions for physics educators at university.

9 Some Illustrations of the Nature of Physics as a Lifelong Pursuit

One of the goals of physics education is to help students appreciate the nature of physics as a lifelong pursuit to understand the physical universe and the world around them. Although the study of physics at university is partly motivated by its career prospects, young people at the interface between school and university physics tend to be idealistic and the following quote from a high school student is quite typical: '*I'd go to university to study physics because I want to study a subject I'm passionate about, taught by people who are just as passionate. Any positive career impact is simply a bonus.*'[7]

Other insights into how physicists go about this lifelong pursuit can be found in the book "Surely you're Joking Mr. Feynman".[8] There are many passages of this book that eloquently express the essence of thinking like a physicist; for example Feynman relates how he has always been motivated by the drive to solve puzzles in

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[7]As told to the author by one of his students

[8]'Surely you're joking, Mr. Feynman!', Richard Feynman (as told to Ralph Leighton), Edited by Edward Hutchings, first published by W.W. Norton 1985 then by Unwin Paperbacks, London, 1986. ISBN 0-04-530023-2.

attempts to understand the universe—he has to keep going until he solves the puzzle.

In one passage, Feynman describes how, as a child, he fixed the radio of a neighbour by thinking about what might be causing it to operate badly; the owner never thought it possible that a little boy could figure out what was wrong by observing and thinking!

In another passage, based on his address to new students at CalTech, he explains the key features of scientific integrity in terms of the need for utter honesty, including thinking about what might be wrong in your theories or experimental results as well as what is new and successful. You must be open about this and also welcome constant questioning and challenge. You must not fool yourself and after that, normal honesty makes it easy not to fool other people. That is crucial.

10 Bibliography

The following three books (intended for a wide readership) give very unusual but enlightening perspectives on some of the issues raised in this paper.

1. "Surely you're joking, Mr. Feynman!", by Richard Feynman (as told to Ralph Leighton), Edited by Edward Hutchings, first published by W.W. Norton 1985 then by Unwin Paperbacks, London, 1986. ISBN 0-04-530023-2. This contains many "gems" which exemplify the essence of the nature and importance of thought processes in physics as expressed by a great physicist. Particularly illuminating passages are to be found in the Chapters, "He Fixes Radios by Thinking" and "Cargo Cult Science" (adapted from his Caltech commencement address, 1974).
2. "Through the Looking Glass, and What Alice Found There", by Lewis Carroll (Charles Dodgson), Published by Macmillan, London, 1871, the sequel to Alice in Wonderland with which it is now often published together. Charles Dodgson was a mathematician at the University of Oxford and there are several passages that indirectly illustrate the nature of mathematical thought and of the problems of giving meanings to words; one particular example which is relevant to the problem of giving meaning to words such as competence is the dialogue between Alice and Humpty Dumpty on "portmanteau" words.
3. "The Curious Incident of the Dog in the Night-Time", by Mark Haddon, published by Jonathan Cape, London, 2003. ISBN 9780099450252. This novel expresses the relation of the internal thought processes of a 17 year old young man with Asperger's syndrome to the external world and how he misunderstands and is misunderstood by those with whom he has to interact. The nature of mathematics as an internal thought process (at which he excels) and also its relation to the physical world are well illustrated. It has been adapted as a moving and highly successful stage play in London and New York and elsewhere.

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