Chapter 1

The development and assessment of problem solving in 21st-century schools

By
Benő Csapó
MTA-SZTE Research Group on the Development of Competencies, University of Szeged, Hungary.
and Joachim Funke
Department of Psychology, Heidelberg University, Germany.

The skills considered most essential in our modern societies are often called 21st-century skills. Problem solving is clearly one of them. Students will be expected to work in novel environments, face problems they have never seen and apply domain-general reasoning skills that are not tied to specific contents. Computerised dynamic problem solving can be used to create just such an interactive problem situation in order to assess these skills. It may therefore form the basis for a type of assessment which helps answer the question of how well schools are preparing their students for an unknown future. This chapter shows how education systems may benefit from such an assessment. It reviews educational methods that have aimed at developing students' higher-order thinking skills and indicates how experiences with these approaches can be used to improve problem solving, from direct teaching, through content-based methods, to innovative classroom processes. It outlines the evolution of large-scale assessment programmes, shows how assessing problem solving adds value and, finally, identifies some directions for further research.

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Introduction

Several features characterise developed societies at the beginning of the 21st century, but two of these have prevailing consequences for schooling: 1) the determining role of knowledge and skills possessed by their citizens; and 2) the rapid changes apparent in all areas of life. Students therfore not only have to master more knowledge to be able to live a successful life in these societies, but they also have to master a different type of knowledge which enables them to succeed in a rapidly changing environment. This means that if schools only prepare their students for current expectations, their knowledge and skills will be outdated by the time they have to use them in their private life and in the world of work.

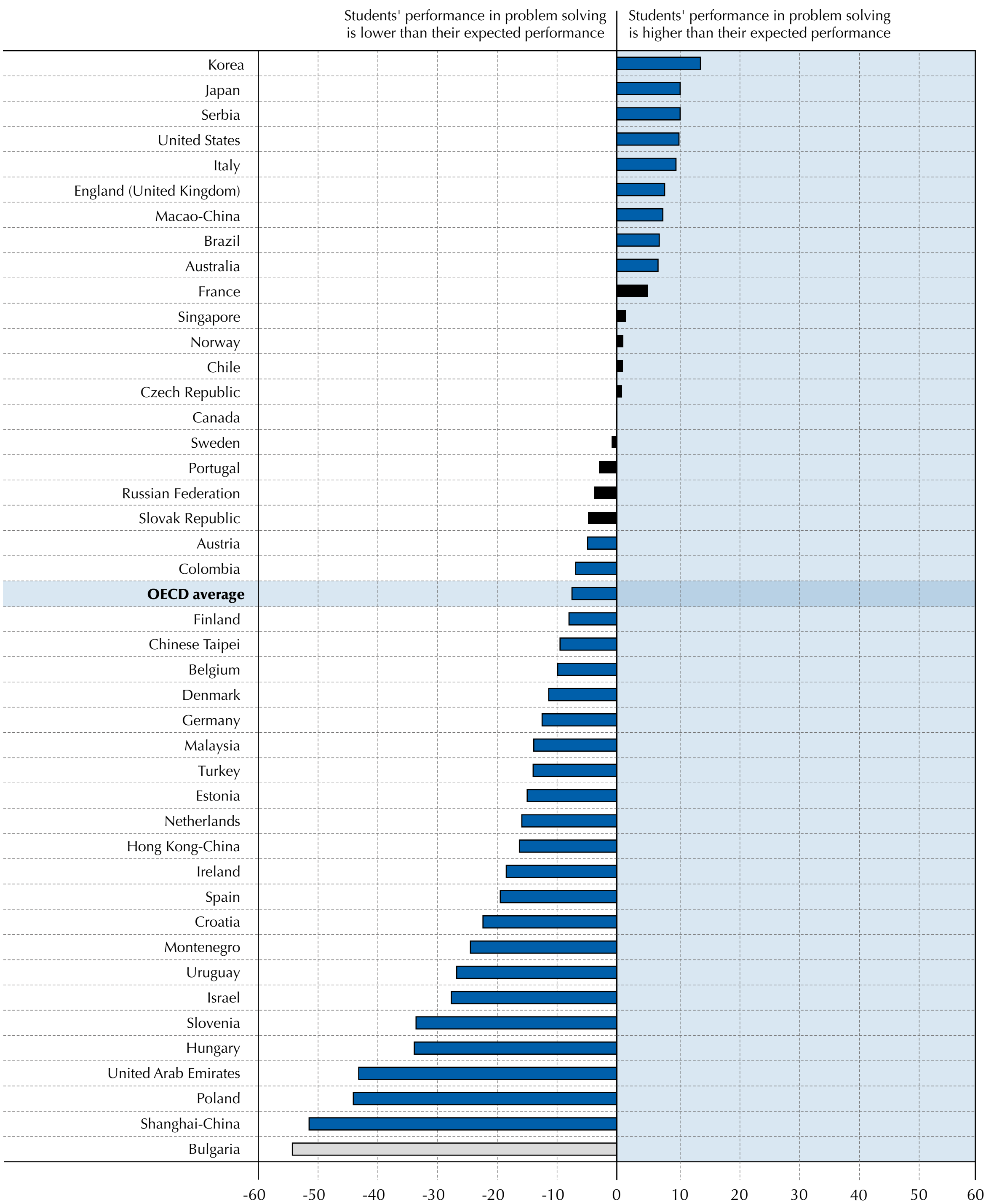
Reflecting these expectations, a new term has emerged in recent decades in the discussion about the goals of education: a family of skills considered the most essential in modern societies, often called 21st-century skills. Lists of these skills usually include creativity, innovation, communication, collaboration, decision making, social skills, cross-cultural skills, information and communications technology (ICT) literacy, civic literacy, media literacy, critical thinking, learning to learn and problem solving (see for example Binkley et al., 2012). However, when these skills are examined in detail, it often turns out that there are very few research results related to some of them, and some of them are difficult to define and specify precisely enough to be measured. Furthermore, in most cases, it is even more difficult to find methods for developing them.

Problem solving stands out in this group as it has been researched for several decades (Frensch and Funke, 1995; Funke and Frensch, 2007; Klieme, 2004; Mayer, 1992). Although problem solving is a general term and the corresponding field of research is very broad, several forms of problem solving are well defined and there are clear distinctions between some of them, for example between domain-specific and domain-general as well as between analytic and complex problem solving (Fischer, Greiff and Funke, 2012; Greiff, Holt and Funke, 2013; Greiff et al., 2013; Wüstenberg, Greiff and Funke, 2012). It is also known from research that complex problem solving, like most complex skills, develops over a long period (Molnár, Greiff and Csapó, 2013; Wüstenberg et al., 2014).

Because of its complex nature and long developmental time, there is little firm evidence showing how different educational methods stimulate its enhancement. The long-term impact of education on other cognitive abilities has been studied since the very beginning of research on intelligence. The general conclusion of such studies is that education improves general cognitive abilities: there is a clear relationship between years spent at school and level of cognitive abilities. A recent longitudinal study indicated that students taking academic tracks made greater gains than those receiving vocational education (Becker et al., 2012); furthermore, the results of a long-term longitudinal study suggest that the impact of education may be subject-specific rather than general (Ritchie, Bates and Deary, 2015). It was the problem solving assessment in the 2012 Programme for International Student Assessment (PISA) which first provided data that demonstrated that there are large differences between educational systems in terms of improving a well-defined cognitive ability.

As problem solving was the fourth (innovative) domain of the 2012 assessment, it was possible to compare the impacts of different education systems on performance in three main domains and on problem solving. The results of these comparisons have shown that even countries which are very good at teaching reading, mathematics and science literacy may be weaker in developing students' problem-solving abilities (OECD, 2014). Figure 1.1 demonstrates these differences. This analysis applied a regression model to predict the problem-solving performance of the countries participating in this assessment, based on their performance in the three main domains. The figure shows the difference between expected levels of problem solving (predicted by the regression analysis) and the measured levels.

Figure 1.1 **Relative performance in problem solving**



Source: OECD (2014), PISA 2012 Results: Creative Problem Solving (Volume V)
Student Skills in Tackling REal-Life Problems
StatLink http://dx.doi.org/10.1787/9789264208070-en, p. 69, Fig. V.2.15.

There are some countries where mathematics, science, and reading performance is high or has improved a great deal in the past decade, for example Shanghai-China and Poland, but problem-solving performance is relatively low. Other countries, such as Korea and Japan, perform well in the main domains and even better in problem solving than could be predicted simply on the basis of their other results. Students from the United States also perform better than expected (Dossey and Funke, 2016). In a country-by-country comparison of performance, a variety of patterns can be identified, clearly indicating that improving problem solving requires something other than teaching the main domains well. In this assessment, about 32% of the variance of problem-solving skills is not explained by the reading, mathematics and science scores. Although the reasons for these differences cannot be precisely identified based on the available data from this assessment, it is clear that the teaching and learning methods used in some countries are more effective at developing problem solving than others.

These results may provide an impetus for research on methods of improving problem solving in an educational context. Although this may be an emerging field of research, the intention of developing cognitive abilities and research in this field is not new at all. Experiences from previous attempts at improving cognitive abilities may also be used in the field of problem solving. In past work, there has been a close interaction between teaching and assessment processes both in research and in educational practice. It is therefore reasonable to also deal with these two aspects of problem solving in parallel. Bloom's classical taxonomies were used both to describe and operationalise educational objectives on the one hand, and as the foundation of assessment instruments on the other (Bloom et al., 1956). In modern educational systems, curricula and assessment frameworks are often developed in parallel. Making cognitive constructs measurable is a precondition for systematic improvement; conversely, the emergence of new teaching methods calls for the development of specific assessment instruments.

Following this logic, the next sections describe the evolution of teaching methods which aim at improving the quality of knowledge and developing higher-order thinking skills, and show how they may serve as models for improving problem solving as well. They then outline the changes in large-scale international assessment, in parallel with those observed in teaching, that enable them to measure newer attributes of knowledge, and summarise the role dynamic problem solving plays in these developments. Finally, the chapter outlines the prospects for assessing and developing problem solving as a result of the PISA assessment and the research it has initiated.

Educational methods aimed at improving the quality of knowledge

Traditional conceptions of learning focused on memorising facts and figures and reproducing them in an unchanged context. Teachers were considered the sources of knowledge, and classroom work was typically teacher-directed. On the other hand, the intentions of cultivating students' minds, preparing them to reason better, and helping them to be able to use their knowledge beyond the school context are as old as organised schooling itself. Although these were the declared goals, they often remained slogans simply because of the lack of scientific background and practical knowledge, and so rote learning dominated everyday practice. Collaboration, creativity and problem solving were also listed among educational goals in the past century, but in reality only a small proportion of students were actually required to apply these skills in their work and in everyday life.

A number of instructional experiments in the 20th century produced remarkable results beyond rote learning, but they failed to spread to entire education systems. As rapid technological, social and economic development at the beginning of this century has made it essential for most citizens to acquire new cognitive skills at a high level in order to find a job in the knowledge economy, these earlier innovations may need to be re-evaluated. This section considers four kinds of earlier or more recent developments which may be relevant to problem solving in education. Although, as the previous section noted, it is not known why some education systems are more successful at developing problem-solving skills than others, the intensity and frequency with which they use these approaches may contribute to their results.

Direct teaching of thinking skills

The rise of research on general cognitive abilities has inspired a number of educational methods aimed at improving these abilities. The first developmental programmes were independent of any school subject and aimed at developing very general cognitive constructs or even intelligence. Depending on the interpretation of general cognitive abilities, it is still disputed which components can be taught and to what extent, if at all. In educational contexts, models of plastic general ability have proved to be more fruitful than the rigid single-factor conception of intelligence. This shift is also supported by recent research in cognitive neuroscience (for an elaboration of this issue, see Adey et al., 2007).

One of the most well-known programmes in this category was Feuerstein's Instrumental Enrichment Program, which was effective in some applications, for example children with special educational needs and socially handicapped students, but did not produce the expected results when more broadly applied (see Blagg, 1991). Klauer devised a series of better-specified intervention programmes for the development of inductive reasoning (based on an operational definition), starting with materials for the direct training of young and handicapped children (Klauer, 1989) and continuing with more broadly applicable training programmes, including the development of problem solving (Klauer and Phye, 1994).

The main difficulty with these direct, independent, stand-alone programmes was that they required specific training (extra efforts beyond the usual instructional processes) which meant they were usually short. Their lasting impact and the transfer of any effects to other skills or broader contexts often remained insufficient. On the other hand, these intervention studies resulted in a number of particular intervention methods and provided rich experiences of aspects of trainability such as the sensitive age, effect size, transfer and duration of effects, which could then be used in designing instructional programmes. Experiments on the direct development of problem solving (such as Kretzschmar and Süß, 2015) may have a similar positive influence on educational applications.

Content-based methods: Integrating the teaching of disciplinary content and improving reasoning

A more fruitful approach seems to be the use of improved teaching materials for developing specific reasoning skills, as the disciplinary materials are there anyway and the time students spend mastering a subject can also be used to improve general cognitive abilities . These approaches are often called infusion methods, embedding or enrichment; each term indicates that some extra developmental effect is added to the traditional instructional processes (see Csapó, 1999 for a general overview of this approach).

Cognitive Acceleration through Science Education (CASE) is one of the best elaborated and most broadly tested developmental programmes in this category (Adey and Shayer, 1994; Adey, Shayer and Yates, 2001). Its embedded training effects not only improve general cognitive abilities, but also aid in a better mastery of science content. It thus meets the requirements of other progressive instructional approaches, such as "teaching for understanding" and "teaching for transfer".

Other content-based methods for developing problem solving use slightly different approaches aimed at developing problem-solving competencies. Problem-based instruction (PBI, see Mergendoller, Maxwell and Bellisimo, 2006 for an example) or problem-based learning (PBL, Hmelo-Silver, 2004; for a meta-analysis of its effects, see Dochy et al., 2003) organise teaching and learning around larger, complex, natural problems which often require active reasoning as well as the mobilisation and integration of knowledge from several traditional school subjects.

These integrated, content-based methods are often used to increase students' interest and motivation. As they are usually implemented within instructional time, they have the potential for broader application. The results of training experiments indicate that durable impacts can only be expected from long-term interventions, and long-term intervention can only realistically be implemented if they use improved (enriched) regular teaching processes.

Enhancing instruction to improve problem-solving abilities

A number of specific improvements in instructional processes which offer the possibility of improving problem solving have also been studied. Implementing them systematically in everyday school processes would have a measurable cumulative impact.

Using representations may contribute to a better understanding of learning materials in general, but representing complex problems properly is the first step in a successful problem solving process. Training students to use representations, especially multiple representations (e.g. depictive and descriptive), and practising the transformations between representations may facilitate the development of problem solving as well (Schnotz et al., 2010). In a similar way, visualisation (for which computerised teaching materials offer excellent opportunities) supports the mastery of content knowledge and at the same time improves problem-solving skills (Wang et al., 2013).

Computer-based simulations of problem situations are an important condition for the assessment of dynamic problem solving, and may be used for developmental purposes as well (e.g. Rivers and Vockell, 2006). Similar to the idea of simulation is gamification or game-based learning. This rapidly developing area of educational technology engages students in well-structured serious games which require them to practise certain reasoning skills. Simulation may help students understand some complicated phenomena, while game-based learning combines learning and entertainment and so makes learning more exciting and improves student perseverance (Connolly et al., 2012; Hwang and Wu, 2012). These methods have been tested for the development of problem solving in a number of different areas and contexts (for example Chang et al., 2012; Rowe et al., 2011; Spires et al., 2011).

A number of studies have shown that training students to better monitor their own learning processes, thus facilitating self-regulated learning and metacognition, may also contribute to the improvement of problem solving (Montague, 2008; Perels, Gürtler and Schmitz, 2005).

Schoenfeld has generalised his work on teaching methods of mathematical problem solving and developed his theory of goal-oriented decision making, which is then applicable in broader teaching contexts, including the improvement of problem solving (Schoenfeld, 2011). He builds on monitoring and self-regulation, which are components of several other innovative methods as well. Metacognition and self-regulated learning help students to develop their own problem-oriented study processes.

Global approaches to improving interest, motivation and the quality of learning

Modern constructivist theories describe learning as an interaction with the environment, with the teacher's role being to provide students with a stimulating physical and social environment and to guide their students through their own developmental processes (e.g. Dumont, Istance and Benavides, 2010). A number of methods to enhance environmental effects have recently been piloted and introduced into educational practice; these are sometimes called "innovative learning environments" (OECD, 2013a) or, if enhanced with ICT, "powerful learning environments"

(De Corte, 1990; De Corte et al., 2003; Gerjets and Hesse, 2004).

Some of these methods have already been introduced into everyday school practices, such as working in pairs and several forms of group work which build on the benefits of social interaction. Collaborative learning, especially its computer-mediated form, also creates excellent opportunities for the development of problem solving (Uribe, Klein and Sullivan, 2003). These types of activities already form a bridge towards collaborative problem solving (e.g. Rummel and Spada, 2005), which was the innovative domain of the PISA 2015 assessment.

Discovery learning builds on students' curiosity and may be very motivating (Alfieri et al., 2011). Similarly, inquiry-based learning takes place through students' active observation and experimentation; inquiry-based science education (IBSE) has recently become especially popular (Furtak et al., 2012). IBSE aims to introduce the basic processes of scientific research into the practices of school instruction. One of its declared goals is to develop scientific reasoning and other higher-order thinking skills by creating and testing hypotheses. This is one of the most broadly studied methods used to revitalise science education; indeed, the European Union has supported more than 20 IBSE projects during the past decade.

Developing the scope of international assessment programmes

Countries' educational cultures differ with respect to the depth and frequency of the application of these approaches to teaching. It seems a plausible hypothesis that the methods described above better prepare students for an unknown future than traditional direct teaching. To test this hypothesis and to measure the cumulative impact of these innovative methods on real learning outcomes, however, also requires the development of innovative assessment instruments. This need initiated the assessment of problem solving in PISA 2003 (OECD, 2005). Nine years later, the development of technology made it possible to overcome the limitations of paper-based assessments for assessing problem-solving skills at the level of education systems. This section provides an overview of how large-scale assessment projects have evolved from the early curriculum-based surveys through the application-oriented conception of literacy to the assessment of higher-order thinking skills.

This overview considers a three-dimensional (curricular content knowledge, application of knowledge and psychological dimension) approach to the goals of learning (Csapó, 2010) and shows how they complement each other.

Curriculum-based content-focused assessments

The first international assessment programmes were the International Association for the Evaluation of Educational Achievement (IEA) studies in the 1970s and 1980s. They were based on an analysis of the curricula of participating countries. Bloom's taxonomies (Bloom et al., 1956) governed the analysis of curricula and the development of assessment frameworks. The content assessed was thus almost identical with what was taught at schools.

However, one of the most obvious experiences of school education is that students usually cannot apply the knowledge they have mastered at school in a new context. In other words, the transfer of knowledge is not automatic. Some traditional forms of teaching result in inert knowledge, as they are not effective in facilitating the application and improving the transfer of knowledge.

These experiences initiated changes in the IEA surveys, and the Trends in International Mathematics and Science Study (TIMSS) assessments, which have been carried out regularly every four years since 1995, measure a broader range of competencies. The most recent framework of TIMSS mathematics and science assessment deals with broad categories such as knowing, applying and reasoning (Mullis and Martin, 2013).

Assessing the application of knowledge

Although assessing the ability to apply knowledge was a goal of early international assessment programmes (Bloom's taxonomy also considers application), they did not elaborate the scope and areas of transfer and application played a secondary role. The cognitive revolution in psychology in the decades preceding the launch of the PISA assessments initiated new directions for research on human information processing as well as for knowledge and skills as outcomes of learning.

These new insights and empirical research results have found their way into educational applications. The OECD"s PISA programme has also drawn from this knowledge base. The OECD's Definition and Selection of Key Competencies (DeSeCo) programme drew on results from the cognitive sciences and interpreted the conception of competencies in the context of school education (Rychen and Salganik, 2001). The first PISA frameworks reinterpreted the conception of literacy and elaborated the definitions of reading literacy, mathematical literacy and scientific literacy as forms of knowledge that are applicable in typical contexts of modern societies.

In sum, the early assessment programmes deduced their frameworks from the knowledge of particular scientific disciplines (science and mathematics), while PISA added a new dimension: the application of knowledge. Literacies – in other words, the conception of broadly applicable knowledge and skills (e.g. PISA assessment frameworks) – can be deduced from the social environments, expectations and demands of modern life. More precisely, it is not what students have been taught, but what they are expected to know that directs the development of frameworks, beyond taking into account the most recent results from cognitive research and research on learning and instruction in general (OECD, 2013b).

Assessing general cognitive skills: The psychological dimensions of knowledge

Neither the knowledge base of mathematics and science and other disciplines, nor the present social demands for applicable knowledge provides a perfect source to determine the skills that will be needed in the future. It seems plausible that students can be prepared for an unknown future by developing their general cognitive skills.

This new need to assess a further dimension of knowledge is marked by the large number of publications dealing with this new future orientation. Some deal with the assessment of higher-order thinking skills (Schraw and Robinson, 2011), 21st-century skills (Griffin and Care, 2015; Mayrath et al., 2012), a variety of competencies (Hartig, Klieme and Leutner, 2008), and, especially, problem solving (Baker et al., 2008; Ifenthaler et al., 2011).

Dynamic problem solving, the innovative domain of PISA 2012, has all the features of such an assessment, evaluating how well students are prepared to solve problems where they do not have ready-made, well-practised routine solutions. Nevertheless, to integrate such a domain into the system of assessments and to develop a framework for it, really requires an anchoring in the psychology of human reasoning: knowledge of human information processing in general, and the psychology of problem solving in particular.

The relevance of assessing problem solving for PISA

When students are expected to work in a novel environment and face problems they have never seen, they cannot use content knowledge they have mastered before but they can apply their domain-general reasoning skills that are not tied to specific content. They have to understand the situation, create a model, and, through interaction with a particular segment of the environment, explore how it responds and behaves. The knowledge gained from this interaction can then be used to build a model, generalise new knowledge and subsequently use it to solve the actual problem.

Computerised dynamic problem solving creates such a problem situation. It may thus form the basis for a type of assessment which helps us to answer the question of how well schools prepare their students for an unknown future.

In a dynamic problem-solving task, students face a system that simulates a real system and behaves similarly to it. The problem-solving process typically has two main phases (see Funke, 2001): a knowledge acquisition phase and a knowledge application phase. Problem solvers have to mobilise a number of operational reasoning skills as well as higher-order thinking skills in both phases. First, they have to understand the simulated system as a whole and then identify the relevant variables of the system. In this phase, they may apply their analogical thinking in search of already known analogous systems. Then they have to manipulate the variables systematically and observe how changing the value of one variable affects the value of other variables. In the meantime, they may use a number of combinatorial and classification operations, propositional reasoning skills, etc. By organising the results of their observations, they induce some rules and test if the rules are valid. When they are convinced that the rules they have just discovered are correct, they begin to apply this newly mastered knowledge. In the knowledge application phase, they may again use a number of further reasoning skills (Greiff and Funke, 2009; Greiff, Wüstenberg and Funke, 2012).

Knowledge acquisition is an important process in learning the content of school subjects, and knowledge application is required for PISA literacy tasks when knowledge mastered in one situation is applied to another one. However, dynamic problem solving assesses students' cognitive skills in a clearer, better-controlled situation, where the results are less masked by the availability of the knowledge students have mastered before.

Conclusions for further research and development

To illustrate the nature of the difficulties we face when we consider the prospects for fostering problem solving in schools, we may use an analogy from physics. We know that nuclear fusion is possible and that it produces immense energy. It is derived from theories of physics, and we know that the sun produces its energy via nuclear fusion. Humans have also created conditions in which nuclear fusion takes place: the hydrogen bomb, which also generates an incredible amount of energy. Thus, it is proven that nuclear fusion works, its mechanisms are known, but we do not have the technology yet that could harness nuclear fusion to produce energy for everyday purposes.

Similarly, even if it is proven that general cognitive abilities are amenable, and the skills underpinning problem solving have already been successfully developed in a number of well-controlled experiments, there is still a long road before we have school curricula and teaching and learning practices that develop problem solving much better than today's schools. Looking back at the history of research on problem solving, we see that the majority of studies have been exploring the mechanisms of problem solving, mostly under laboratory conditions and with simple static tasks. Tests that are usable in an educational context are a recent development, although the availability of good measurement instruments is a precondition for the design of intervention experiments and controlled implementation of large-scale developmental programmes. The PISA 2012 assessment is a ground-breaking enterprise from this perspective, as it demonstrates the possibilities of computer-based assessment in a number of different educational systems.

For now, researchers should first outline a roadmap of research that would produce evidence for the improvement of practice. Such a map would probably include the study of school practices in countries which perform better in problem solving than expected on the basis of their achievement in the main domains (see Buchwald, Fleischer and Leutner, 2015, who discuss a "cognitive potential exploitation hypothesis"). Although it is very difficult to import good practices from one complex educational culture into another, a deeper understanding of how schooling helps students to become better problem solvers in one country may help to improve practices in other countries as well.

Studying the structure and development of problem solving in an educational context also still offers a great deal of potential. Cross-sectional assessments with a large number of background variables may produce results in a short period. In particular, understanding the role of precursors and the early development of component skills may be beneficial, as recent research has underscored the importance of early development. Longitudinal studies, on the other hand, may take a longer time but provide data on real developmental trajectories. Studying the factors that determine development should include a broad range of affective variables.

Finally, experiments for developing problem solving in real educational contexts should be encouraged. Taking into account the multi-causal character of such development, it will be impossible to find a single, simple solution. Experiences from former programmes for developing other higher-order thinking skills suggest that stable outcomes may only result from continuous stimulation of cognition over a long period. As there is no reasonable way to teach problem solving in separate courses, the most promising solutions are those that embed training in problem solving into regular school activities. A number of intervention points should be explored, including standards, assessment frameworks, textbooks, classroom practices and extra-curricular activities. Technology may again be helpful in this matter: simulation and gamification, especially online educational games, may offer unexplored potential for developing problem solving.

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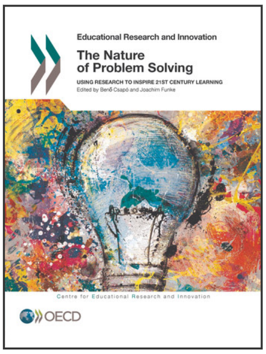

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