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A look at complex problem solving in the 21st century

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EDUCATION: FUTURE FRONTIERS

EDUCATION: FUTURE FRONTIERS is an initiative of the NSW Department of Education exploring the implications of developments in AI and automation for education. As part of the Education: Future Frontiers Occasional Paper series, the Department has commissioned essays by distinguished authors to stimulate debate and discussion about AI, education and 21st century skill needs. The views expressed in these essays are solely those of the authors.

21st century skills are skills that are considered important for being able to face current and future global challenges and challenges in work-life. Complex Problem Solving (CPS) is one of the most prominent 21st century skills in educational settings because it is related to important outcome variables such as academic success, and recent research has provided indications of the malleability of CPS.

A brief introduction to 21st century skills in educational settings: The example of complex problem solving

The world is changing, and the next generation will face new social, economic and environmental challenges. The relevance of routine tasks continues to decline, whereas problem solving, teamwork and communication are becoming increasingly important in modern societies (Autor, Levy, & Murnane, 2003). In addition to the skills that have already been the focus of educational research and practice, such as literacy, mathematics and science, educators have now begun to identify other skills that are necessary to handle these new challenges—known as 21st century skills (National Research Council, 2012). Unlike the classical academic skills that mainly involve the memorisation and reproduction of specific information and knowledge (Kereluik et al., 2013), 21st century skills are more transversal, focusing on the acquisition, combination and application of knowledge.

A prominent example of a 21st century skill is Complex Problem Solving (CPS). CPS describes the process of solving problems that resemble real-life situations. For example, figuring out how to use a new smartphone for the first time without any instructions constitutes a complex problem. The initial configuration or default settings of the smartphone require the user to explore the vast number of available and — at least partly — unknown options as well as their relations to each other. No specific previously learned knowledge will assist the user but rather the skill to acquire new knowledge about the smartphone by interacting with it. This new knowledge can be applied to find a desired menu or to play music.

Complex problem solving - a definition

Complex Problem Solving (CPS) describes the successful interaction with complex systems targeted at reaching a desired goal state or a problem solution. An example, studying at a university, can demonstrate how a complex system or problem has five core attributes (Funke, 2001):

- The complexity of the problem requires the problem solver to reduce a large amount of available information in order to make decisions. For example, while studying, a student needs to organise the material from his/her courses to prepare for tests.
- The connectivity of the variables in the system means that the variables can be directly or indirectly interrelated, and hence, changes in one variable can influence others. Connectivity during studying is based on specific prerequisites of some academic courses or possible specialisations that require basic courses.
- A system's dynamics require the problem solver to consider time as a relevant factor because the system acts and reacts over time. The dynamics of studying can involve learning effort,

which might also be influenced by a learner's motivation. These are attributes of studying that can vary over time.

- The intransparency of a system means that not all of the relevant information for a successful interaction is provided at the beginning. While studying, even if the general topic of a test is usually known, the specific focus is not and may require students to be flexible in their preparation and ideally be able to identify possible areas of focus in advance in order to be efficient.
- The polytely of a complex system describes the existence of several different goals that might even be contradictory. The limited amount of time available for studying requires students to prioritise their activities, such as learning, meeting friends or pursuing hobbies.

Relevance of 21st century skills

The label 21st century skills is used to describe an entire set of important skills that are required to successfully face the challenges of the 21st century. The relevance of some of these skills (e.g. collaboration) has been acknowledged in the past but in recent decades the recognition of their importance for everyday tasks has increased considerably. Broad skills rather than specific knowledge have become increasingly important. At the same time it is understood that entirely new skills (e.g. digital literacy) are also now required to succeed.

In addition to purely knowledge-based skills, 21st century skills are methods or tools that are aimed at acquiring and managing knowledge. The current focus on 21st century skills has been amplified because more factual knowledge is now readily available. For example, car repair does not require the mechanic to know all the details about the specific car model as the information is available in the (electronic) manual provided by the manufacturer, but the mechanic needs to be able to identify and solve problems. It is therefore the acquisition and use of knowledge about how to cooperate and solve problems rather than the knowledge itself that puts 21st century skills in the focus of modern education (National Research Council, 2012). Obviously, many tasks still require specific knowledge, and even the best problem solver will not automatically be an expert mechanic. Nonetheless, the teaching and assessment of 21st century skills such as CPS are important to understand.

The empirical evidence and theoretical foundation of 21st century skills are mixed. Some, such as CPS, are well-founded in substantial research. Others — on which research has just begun to focus quite recently — are mainly based on theoretical considerations and plausibility and not so much on existing and accumulated empirical evidence. However, any sound recommendations for educational practitioners and policy makers should focus on well-established 21st century skills that have been found to be related to important outcome variables such as academic or work success. Such recommendations should also be based on the current state of research.

Complex problem solving: what we know and what we don't know

CPS is an example of a relevant and much discussed 21st century skill as it is an already well-established construct that is related to important outcome variables such as academic achievement. In fact, CPS has been widely discussed in educational policy circles.

CPS was introduced in the late 1970s by Dietrich Dörner due to an assumed lack of realism in existing

problem solving approaches (for a summary of the early research in this area, see Frensch & Funke, 1995). Dörner criticised the classical approach to problem solving (as still used in most measures of intelligence) as too static. He noted that real problems usually neither have a single valid solution, nor do they reveal all the information necessary for their solution from the very beginning. To reduce this discrepancy between problems in reality and existing problem solving approaches, he defined CPS as the process of solving problems that are not static but that change over time, allow for multiple valid solutions, and require active exploration before they can be solved (e.g. Dörner et al., 1983).

The increasing importance of CPS as a 21st century skill has created a need for continuous research on CPS as well as new assessment approaches. The aim to describe and assess problem solving more realistically remains the driving force behind current CPS research. However, the first CPS approaches might have been too complex because the sheer number of variables involved (ranging from dozens to thousands) increased the duration of assessments as well as the impact of chance and thus lowered the general validity of such approaches.

The assessment of such an interwoven skill as CPS requires the use of computer programs that can simulate complex real-world problems (e.g. running a company, a little town or even a whole country) as realistically as possible. Current approaches to the assessment of CPS aim at improving the validity of the assessment by reducing the number of variables and by using more than one kind of measurement while still including some important aspects of real-life problems. More specifically, many complex problems found in assessments today do not provide all the necessary information from the beginning (intransparency) or include multiple ways in which the problem can be solved. Multiple variables (complexity) that can be related to each other (connectivity) might be involved, and the final goal or set of goals may be unclear or contradictory (polytely). In addition, real problems can change due to the problem solver's actions (dynamics) or over time. To avoid distortions caused by prior knowledge about a subject (e.g. business), modern CPS assessments often use rather arbitrary or very unusual cover stories. These aspects are used to implement problems that are closer to reality than most classical problem solving approaches but still provide valid measurement results. They are generally accepted in the scientific community (e.g. Fischer, 2015; Funke, 2006; Greiff & Funke, 2009) and are compatible with alternative approaches to identify relevant aspects of real-life problems (e.g. Sterman, 2003).

Evidence supporting the relevance of CPS for education and educational policy

Most research has shown that CPS is strongly related to academic success and other performance indicators in school (Greiff et al., 2013; Lotz, Sparfeldt, & Greiff, 2016) and university (Stadler et al., 2016). In a recent study, Kyllonen, Carrasco, and Kell (2017) showed that experts put a higher value on CPS than on a more general cognitive performance measure in almost 700 occupations, even if domain-specific knowledge is excluded. The adequacy of CPS training and assessment in educational settings is therefore evident, due to its demand in education, economics and society.

Whereas performance measures such as intelligence tests often appear to be more or less stable and resistant to changes in the environment (Rönnlund, Sundström & Nilsson, 2015), current research suggests that CPS might be malleable. More specifically, strategies that are required for CPS such as the vary-one-thing-at-a-time (VOTAT) strategy can be trained

What describes a good problem solver?

Strategies and procedures that are advantageous in problem solving:

- Taking a breath: A good problem solver stays calm, even in stressful situations.
- Keeping track: Having an overview of the situation and the context helps good problem solvers prioritise tasks and reduce vast amounts of information to the most important points.
- Working strategically, if possible: Good problem solvers aim to identify and analyse the important variables and try to gain control over the complex situation by using adequate strategies.
- Evaluating actions and adapting: Possible sudden changes of the situation and the relations of variables should be considered. Hence, interactions with the situation should be evaluated and, if applicable, the problem solver's internal representation of the model should be updated.

Remaining cognitively flexible and being able to thoroughly analyse the problem is advantageous for problem solving in general and CPS in particular (Krems, 1995). People can be trained to improve their problem solving — even for people for whom problem solving is not intuitive and even if transferability is not guaranteed (Bassok, 1990; Chen & Klahr, 1999; Kretzschmar & Süß, 2015).

and can lead to performance gains. The VOTAT strategy (also known as "control of variables"; Shayer 2008) describes the process of minimising the influence of all but one variable in a system in order to determine the role of this variable. This strategy represents the basis for all scientific discovery and is an essential part of CPS because complex problems require the problem solver to understand the problem situation in order to subsequently apply the acquired knowledge. Teaching students this strategy will thus also help them to solve complex problems in CPS assessment, science and everyday life.

Further improvements or developments in the field of CPS are expected in future research. For instance, one can easily explain what a complex problem is, how it can be solved, and what successful CPS is related to. However, it is less clear how CPS functions on a cognitive level such as how it is related to specific facets of intelligence or working memory capacity. Carefully relying on existing empirical evidence regarding the advantages of CPS currently allows it to be applied in education. In the long run, however, an explanation and clear(er) definition of CPS is required to ensure the adequacy of the application of CPS with a profound theoretical basis.

Complex problem solving in action

The dynamic nature of CPS tasks means that the teaching, learning and assessment of CPS most often requires the use of computers. The defining characteristics of complex problems such as connectivity and dynamics are implemented by using computer-based problem environments. Therefore, the relations with and the functionality of the variables of a complex problem must be identified and then used to solve the problem to work toward a desired goal-state. This use of gamified assessments in CPS increases acceptance and hence the motivation among participants (Sonnleitner et al., 2012).

On a practical level, CPS has already been included in several educational large-scale assessments.

Most prominently, the Organisation for Economic Co-operation and Development (OECD) compared the CPS performance of 15-year-old students of its member states in the international large-scale assessment Programme for International Student Assessment (PISA) in 2012. Across the 35 OECD member states as well as several additional non-member states, students were asked to participate in a computer-based CPS test.

In this 2012 PISA study, Australia was part of the top five of all OECD countries in which students performed higher than students in other countries despite similar results in science, reading and mathematics. That is, even if students in other countries achieved similar results in the three "classical" fields, their CPS performance was significantly lower than the performance of Australian students. This implies that 21st century skills and especially CPS might already be a relevant part of the national curriculum in Australia and that, in an international comparison, Australian students are particularly well equipped with CPS skills.

When interpreting the countries' average results, it is important to also consider the distribution of performances leading to these averages. The good CPS results of some countries such as Australia, the United States or the United Kingdom mainly derive from students who also performed highly in the three classical areas of science, reading and especially mathematics (OECD, 2014). In other high-performing countries such as Japan on the other hand, students preforming moderately and low performing in science, mathematics and reading were able to achieve higher results in CPS than expected. In these countries, low-performing students could apparently demonstrate their skills more effectively in the less culturally determined CPS tasks.

The advantages of CPS over more traditional assessments described above make them easy for practitioners to use. Moreover, the systematic exploration of new problems as well as critical (self-) evaluation and meta-skills are clearly an important part of several 21st century skills. CPS might be a method that can be applied to handle some challenges and hence might encourage people to face these challenges

PISA 2012 Problem Solving Results

Country	Points
South Korea	561
Japan	552
Canada	526
Australia	523
Finland	523
United Kingdom	517
Estonia	515
Germany	509
Belgium	508
United States	508
Austria	506
Norway	503
OECD Average	500
Ireland	498
Denmark	497
Portugal	494
Sweden	491
Slovak Republic	483
Poland	481
Spain	477
Slovenia	476

Retrieved from https://nces.ed.gov/surveys/pisa/idepisa/report.aspx

CPS task embedded in a computer simulation

In this task, the participant takes on the role of a record executive striving to increase a record label's sales, popularity and earnings. To do so, the participant can invest in advertising, networking or fan projects. The graphs depict the changes in the system resulting from the participants' interactions.

Simple computer game simulations can be used to assess CPS. However, the training of CPS needs to be implemented in meaningful contexts and situations. That is, the implementation of CPS in educational settings should be presented as part of subjects and topics that are already part of the school or university curricula. The example scenario involves three input variables (at the top with a slider on the bottom) and three output variables. To facilitate the investigation of, and the interaction with, the complex problem, the progress of variables' values is displayed graphically and indicated by the current values. The example presented here can be tried at https://thku.github.io/nsw-cps-item/. The source code and documentation are published under a free and Open Source license at https://github.com/thku/nsw-cps-item/.

Implications for practitioners

In educational practice, the current state of research findings on 21st century skills can be implemented at several levels such as educational institutions or on the more specific course level. At a classroom level, these suggestions might be helpful:

- An atmosphere that supports students to explore, apply and improve the skills they have learned should be created;
- The skill should be explicitly taught, modeled, and examined by the instructor;
- The transfer from one domain to another should be included into the curriculum to avoid having only domain-specific applications;
- Besides teaching, the application of 21st century skills and the related strategies should — if possible — be integrated into the instructions.

Implications for educational systems

While research on 21st century skills is still ongoing, CPS and other 21st century skills have found their way into national curricula (National Research Council, 2012). CPS is strongly related to academic success and other problem solving measures. The successful teaching of 21st century skills such as CPS can thus improve the chances of low-performing students to successfully participate in society in the future because these higher-order skills are in high demand and might help students to later acquire relevant knowledge for their chosen professions.

A profound education is the best way to prepare a young generation to face the problems and the challenges that life will present in the future. High quality education not only impacts on the cognitive abilities of students but has been shown to be a protective factor against poverty and other challenges and should be reasonably expected to offer the best possible preparation for the future challenges of the 21st century.

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