



Educational Research and Innovation

The Nature of Problem Solving

USING RESEARCH TO INSPIRE 21ST CENTURY LEARNING

Edited by Benő Csapó and Joachim Funke



Centre for **Educational Research and Innovation**

Educational Research and Innovation

THE NATURE OF PROBLEM SOLVING

USING RESEARCH TO INSPIRE
21ST CENTURY LEARNING

Edited by Benő Csapó and Joachim Funke

This work is published on the responsibility of the Secretary-General of the OECD. The opinions expressed and arguments employed herein do not necessarily reflect the official views of the OECD member countries.

This document and any map included herein are without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Please cite this publication as:

Csapó, B. and J. Funke (eds.) (2017), *The Nature of Problem Solving: Using Research to Inspire 21st Century Learning*, OECD Publishing, Paris. <http://dx.doi.org/10.1787/9789264273955-en>

ISSN: 2076-9660 (print)
ISSN: 2076-9679 (online)

The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

Photo credits:

Fotolia/alphaspirit

Corrigenda to OECD publications may be found on line at: www.oecd.org/publishing/corrigenda.

© OECD 2017

This work is available under the Creative Commons Attribution-NonCommercial-NoDerivatives 3.0 IGO license (CC BY-NC-ND 3.0 IGO) <http://creativecommons.org/licenses/by-nc-nd/3.0/igo/deed.en>, you are free to copy and redistribute the material, provided the use is for non-commercial purposes, under the following conditions: Attribution - Please cite the work as follows: OECD (2017), *The Nature of Problem Solving, Using Research to Inspire 21st Century Learning*, OECD Publishing, Paris. DOI: <http://dx.doi.org/10.1787/9789264273955-en>. License: Creative Commons Attribution CC BY-NC-ND 3.0 IGO.

Third-party content - The OECD does not necessarily own each component of the content contained within the work. Therefore, the OECD does not warrant that the use of any third-party owned individual component or part contained in the work will not infringe on the rights of those third parties. The risk of claims resulting from such infringement rests solely with you. If you wish to re-use a component of the work, it is your responsibility to determine whether permission is needed for that re-use and to obtain permission from the copyright owner. Examples of components can include, but are not limited to, tables, figures, or images. Requests for permission to use or translate portion(s) of this work for commercial purpose must be obtained through the Copyright Clearance Centre, Inc. CCC, www.copyright.com. Requests for permission to translate or distribute modified version of this work must be submitted to ceri.contact@oecd.org.

Foreword

The demands on learners and thus education systems are evolving fast. In the past, education was about teaching people something. Now, it's about making sure that students develop a reliable compass and the navigation skills to find their own way through an increasingly uncertain, volatile and ambiguous world. These days, we no longer know exactly how things will unfold, often we are surprised and need to learn from the extraordinary, and sometimes we make mistakes along the way. And it will often be the mistakes and failures, when properly understood, that create the context for learning and growth. A generation ago, teachers could expect that what they taught would last a lifetime for their students. Today, teachers need to prepare students for more rapid economic and social change than ever before, for jobs that have not yet been created, to use technologies that have not yet been invented, and to solve social problems that we don't yet know will arise.

The dilemma for educators is that the kind of skills that are easiest to teach and easiest to test, are also the skills that are easiest to digitise, automate and outsource. There is no question that state-of-the-art disciplinary knowledge will always remain necessary. Innovative or creative people generally have specialised skills in a field of knowledge or a practice. And as much as “learning to learn” skills are important, we always learn by learning something. However, success in life and work is no longer mainly about reproducing content knowledge, but about extrapolating from what we know and applying that knowledge in novel situations. Put simply, the world no longer rewards people just for what they know – Google knows everything – but for what they can do with what they know. Problem solving is at the heart of this, the capacity of an individual to engage in cognitive processing to understand and resolve problem situations where a method of solution is not immediately obvious.

Conventionally our approach to problems in schooling is to break them down into manageable pieces, and then to teach students the techniques to solve them. But today individuals create value by synthesising disparate parts. This is about curiosity, open-mindedness, making connections between ideas that previously seemed unrelated, which requires being familiar with and receptive to knowledge in other fields than our own. If we spend our whole life in a silo of a single discipline, we will not gain the imaginative skills to connect the dots, which is where the next invention will come from.

Perhaps most importantly, in today's schools, students typically learn individually and at the end of the school year, we certify their individual achievements. But the more interdependent the world becomes, the more we rely on great collaborators and orchestrators who are able to join others to collaboratively solve problems in life, work and citizenship. Innovation, too, is now rarely the product of individuals working in isolation but an outcome of how we mobilise, share and link knowledge. So schools now need to prepare students for a world in which many people need to collaborate with people of diverse cultural origins, and appreciate different ideas, perspectives and values; a world in which people need to decide how to trust and collaborate across such differences; and a world in which their lives will be affected by issues that transcend national boundaries. Expressed differently, schools need to drive a shift from a world where knowledge is stacked up somewhere depreciating

rapidly in value towards a world in which the enriching power of collaborative problem-solving activities is increasing.

These shifts in the demand for knowledge and skills are well understood and documented, and to some extent they are even intuitive. Not least, many school curricula highlight the importance of individual and social problem-solving skills. And yet, surprisingly little is known about the extent to which education systems deliver on these skills. This is not just because school subjects continue to be shaped by traditional disciplinary contexts. It is also because educators have few reliable metrics to observe the problem-solving skills of their students - and what doesn't get assessed doesn't get done.

The OECD Programme for International Student Assessment (PISA) sought to address this. Its 2012 assessment contained the first international metric of individual problem-solving skills and the 2015 assessment took this further, assessing collaborative problem-solving skills. The results turned out to be extremely interesting, in part because they showed that strong problem-solving skills are not an automatic by product of strong disciplinary knowledge and skills. For example, Korea and Japan, which both did very well on the PISA mathematics test, came out even stronger on the PISA assessment of problem-solving skills. In contrast, top mathematics performer Shanghai did relatively less well in problem solving. Such results suggest that it is worth educators devoting more attention to how problem-solving skills are developed both in disciplinary and cross-disciplinary contexts.

But while problem solving is a fairly intuitive and all-pervasive concept, what has been missing so far is a strong conceptual and methodological basis for the definition, operationalisation and measurement of such skills. This book fills that gap. It explores the structure of the problem-solving domain, examines the conceptual underpinning of the PISA assessment of problem solving and studies empirical results. Equally important, it lays out methodological avenues for a deeper analysis of the assessment results, including the study of specific problem-solving strategies through log-file data.

In doing so, the book provides experts and practitioners with the tools to better understand the nature of problem-solving skills but also with a foundation to translate advanced analyses into new pedagogies to foster better problem-solving skills.



Andreas Schleicher

*Director for Education and Skills
Special Advisor to the Secretary-General*

Acknowledgements

Thanks to all the people who contributed to this book and helped to finalise a process that took much longer than expected! Special thanks to Julia Karl (Heidelberg) who helped us preparing a standardised and printable version of all manuscripts. And thanks to Marion Lammarsch (Heidelberg) for help with converting text from LaTeX to Word. Thanks to the OECD staff, in particular Francesco Avvisati, Sophie Limoges and Rachel Linden, for their valuable support during the production process, and to Sally Hinchcliffe for the thoughtful language editing of the manuscript.

This book stems mainly from the collaboration of the members of the OECD Problem Solving Expert Group (PEG) of PISA 2012. This PEG group started its works in 2009 and finished their official work in 2014. The group consisted of the following eight members:

- Joachim Funke (Chair), Heidelberg University, Germany
- Benő Csapó, University of Szeged, Hungary (ex officio PGB representative)
- John Dossey, Illinois State University, United States
- Art Graesser, University of Memphis, United States
- Detlev Leutner, Duisburg-Essen University, Germany
- Richard Mayer, University of California, United States
- Tan Ming Ming, Ministry of Education, Singapore
- Romain Martin, University of Luxembourg, Luxembourg

Members of the PEG group have already been involved with problem solving for a long time, and their meetings under the umbrella of the PISA work inspired a number of other meetings and co-operative studies involving people from other organisations and institutions. Influenced by the creative atmosphere of the PEG meetings, some of the members met and presented their work together at other professional meetings as well. Amongst these were the annual meetings at Szeged University in the framework of Szeged Workshop of Educational Evaluation (SWEE; since 2009 a yearly repeated event), the TAO days in Luxemburg (March, 2011), the AERA meeting in New Orleans (April, 2011), two symposia at the EARLI biennial meeting in Exeter (September, 2011), the European Conference of Psychology in Istanbul (July, 2011), two symposia at the International Conference on Psychology in Cape Town (July, 2012), and more recently the “Celebrating Problem Solving” conference at the University of Szeged (November 2015). Many related journal articles have been published in the meantime – too many to be listed here.

These productive meetings brought together researchers interested in problem solving, assessment of cognitive skills, and technology based assessment, and so initiated empirical works in the overlapping areas of these special fields. For example, as already mentioned, one of

the major shifts from PISA 2003 problem solving to PISA 2012 problem solving was the shift from paper-and-pencil based to computer-based assessment that required strong interactions between item developers and the group taking care of the technical implementation. Within a rather short time scale, software tools had to be developed and implemented that allow for the necessities in international large-scale assessment studies (e.g. preparing for more than 100 different languages, different character sets including left-to-right and right-to-left, and different levels of computer equipment).

The PEG group was supported by a wonderful team from ACER (Australian Council for Educational Research, Melbourne, Australia): the “trio” consisting of Barry McCrae, Ray Philpot, and Dara Ramalingam. They prepared meetings and materials in a fantastic way and helped us through a jungle of dates, deadlines, and data. Ray Adams worked as Interim Chair in the beginning of the project. All of this contributed to the success of PISA 2012.

Maybe unique in the history of PISA expert groups, this community of researchers, while developing the assessment framework and creating the instruments discovered the potentials of an emerging field: the possibilities offered by computerised, dynamic, interactive assessment of problem solving. Using multimedia and simulation to present the test tasks, capturing students’ responses in novel ways, logging student’s activities and using log-file analyses for exploring cognitive processes, perseverance and motivation have opened new and exciting directions for research. They have been continuing their collaboration far beyond their task in the 2012 assessment cycle.

The individual chapters in this book have been reviewed by members of the group and by reviewers from the OECD. This process hopefully helped to improve the quality of the chapters. At the same time, these activities delayed the publication process a bit.

Lastly we would like to extend our thanks to Andreas Schleicher for his support throughout the publication process.

Table of contents

PART I Problem solving: Overview of the domain.....	17
CHAPTER 1 The development and assessment of problem solving in 21st-century schools.....	19
Introduction.....	20
Educational methods aimed at improving the quality of knowledge	22
Developing the scope of international assessment programmes	25
Conclusions for further research and development.....	27
References.....	28
CHAPTER 2 Analytical problem solving: Potentials and manifestations	33
Introduction.....	34
Analytical problem solving as a process	36
Analytical problem solving as a competence	36
Training in analytical problem-solving competence	40
Summary and discussion	42
References.....	43
CHAPTER 3 Problem solving: Understanding complexity as uncertainty	47
Introduction.....	48
Complex problem solving: Everyday examples.....	49
Complex problem solving: Empirical examples.....	50
Complexity by any other name: Uncertainty	51
Cues to controllability.....	53
Practical solutions to practical problems	55
References.....	56
CHAPTER 4 Problem solving from a mathematical standpoint.....	59
Introduction.....	60
Mathematicians’ views of problem solving	60
What is a problem?.....	61
The role of problem solving in the development of mathematics	63
Students’ problem solving as viewed through PISA	64
The role of metacognition in mathematical problem solving	66
References.....	70

PART II Dynamic problem solving as a new perspective.....	73
CHAPTER 5 The PISA 2012 assessment of problem solving.....	75
Introduction.....	76
Major issues identified.....	76
Evolution of the new problem-solving framework	78
The key features of the PISA 2012 problem-solving framework	81
Developing the consistency	82
Examples of test material.....	85
Conclusion.....	86
Notes.....	87
References.....	87
Annex 5.A1. The PISA 2012 Problem Solving Expert Group	90
Annex 5.A2. Countries and partner economies participating in the OECD PISA 2012 problem-solving assessment	91
CHAPTER 6 Interactive problem solving: Exploring the potential of minimal complex systems.....	93
Introduction.....	94
Interactive problem solving	95
Measuring interactive problem solving.....	96
The philosophy behind minimal complex systems	97
The basic elements of minimal complex systems.....	98
Common elements of MicroDYN and MicroFIN.....	100
Recent results on interactive problem solving.....	101
Discussion.....	101
Notes.....	103
References.....	103
CHAPTER 7 The history of complex problem solving	107
Introduction.....	108
Human failures and strategies.....	109
Cognitive theories on the process of solving complex problems	110
Assessment of complex problem solving.....	112
Discussion.....	114
Trends for future research.....	116
Notes.....	116
References.....	117
PART III Empirical results	123
CHAPTER 8 Empirical study of computer-based assessment of domain-general complex problem-solving skills	125
Introduction.....	126
Technology-based assessment and new areas of educational assessment.....	126
From static to dynamic problem solving with reference to reasoning skills	127
Aims.....	128
Methods	128
Results.....	130

Discussion.....	134
Notes.....	137
References.....	137
CHAPTER 9 Factors that influence the difficulty of problem-solving items.....	141
Introduction.....	142
Characteristics that might influence task difficulty.....	142
The study	146
Described levels for task characteristics	146
Sample items with ratings	149
Analysis and results	151
Discussion.....	155
Possible improvements and future directions.....	156
Conclusion.....	156
Notes.....	156
References.....	157
CHAPTER 10 Assessing complex problem solving in the classroom: Meeting challenges and opportunities.....	159
Introduction.....	160
The Genetics Lab: A microworld especially (PS) developed for the classroom	160
Challenge 1 – Digital natives	163
Challenge 2 – Scoring	167
Summary and outlook	170
Notes.....	171
References.....	171
PART IV New indicators	175
CHAPTER 11 Log-file data as indicators for problem-solving processes.....	177
Introduction.....	178
What are log files?	178
A theoretical rationale for analysing log files in problem-solving assessments.....	179
Analysis of log files.....	183
Discussion.....	187
Concluding remarks	188
References.....	188
CHAPTER 12 Educational process mining: New possibilities for understanding students’ problem-solving skills.....	193
Introduction.....	194
Background: From logs to knowledge.....	194
Analysing problem-solving behaviour data: Educational process mining.....	197
Objectives.....	197
Applying process mining to problem-solving behaviour data	197
Implications for online problem-solving assessment	206
References.....	207

CHAPTER 13 EcoSphere: A new paradigm for problem solving in complex systems	211
Introduction.....	212
The EcoSphere.....	212
The EcoSphere program: BioSphere scenario.....	216
Outlook and conclusion.....	220
References.....	221
PART V Future issues: Collaborative problem solving	225
CHAPTER 14 Assessment of collaborative problem-solving processes.....	227
Introduction.....	228
Collaborative problem-solving skills: A framework for understanding.....	229
Use of the collaborative problem-solving framework	232
Assessing collaborative problem solving	236
Analysis.....	238
Discussion.....	240
References.....	241
CHAPTER 15 Assessing conversation quality, reasoning, and problem solving with computer agents.....	245
Introduction.....	246
Learning environments with conversational agents.....	247
Conversational dialogues with AutoTutor.....	249
Dialogues.....	252
Closing comments.....	256
References.....	257
PART VI Finale	263
CHAPTER 16 Epilogue.....	265

Figures

Figure 4.1	Problem Situation.....	62
Figure 4.2	A pair of students' problem-solving activities over time	68
Figure 4.3	A mathematician's problem-solving activities over time	68
Figure 4.4	A pair of students' activity-time allocation after a problem-solving course.....	69
Figure 5.1.	MP3 player: Stimulus information.....	85
Figure 5.2.	MP3 player: Item 1	85
Figure 5.3.	MP3 player: Item 2	85
Figure 5.4.	MP3 player: Item 3.....	86
Figure 5.5.	MP3 player: Item 4	86

Figure 6.1	Structure of a MICS system with two exogenous and two endogenous variable	99
Figure 6.2	A simple finite state automaton	99
Figure 7.1	Screenshot of a simulation of the complex Moro problem.....	110
Figure 7.2	Screenshot of the Tailorshop problem	113
Figure 7.3	Screenshot of the finite state machine HEIFI.....	115
Figure 8.1	Example of tasks in the domain-specific problem-solving test	129
Figure 8.2	Example of tasks in the inductive reasoning test	129
Figure 8.3	Developmental curve of dynamic problem solving.....	132
Figure 8.4	Developmental curve of dynamic problem solving by school type	132
Figure 8.5	Correlations between inductive reasoning, intelligence, domain-specific and domain-general problem solving.....	133
Figure 9.1.	Birthday Party: Stimulus interactive area	150
Figure 9.2.	Birthday Party: Information provided	150
Figure 9.3.	Dendrogram showing clustering of 10 item characteristics	153
Figure 10.1.	Genetics Lab Task 1: Exploring the creature	161
Figure 10.2.	Genetics Lab Task 2: Documenting the knowledge	162
Figure 10.3.	Genetics Lab Task 3: Changing the characteristics	162
Figure 10.4.	Start screen for a creature	164
Figure 10.5.	Feedback on performance at the end of an item	165
Figure 10.6.	Adapted test development process of the Genetics Lab	165
Figure 10.7.	ICT familiarity and competence of students	166
Figure 10.8.	Acceptance of the Genetics Lab among students	166
Figure 11.1.	Interactive Laughing Clowns task (the clown’s mouth is in constant motion)	179
Figure 11.2.	Sample log-file record from a text file recorded by the interactive Laughing Clowns task	179
Figure 11.3.	Temporal evidence map segment illustrating hypothetico-deductive reasoning from the single-player Laughing Clowns task	184
Figure 11.4.	Temporal evidence map segment illustrating typical exploratory behaviour by novice problem solvers from the single-player Laughing Clowns task	185
Figure 11.5.	Temporal evidence map segment illustrating guessing behavior from the single-player Laughing Clowns task	186
Figure 11.6.	Temporal evidence map segment illustrating uncertainty about the problem from the single-player Laughing Clowns task	186
Figure 12.1.	Web search item.....	195
Figure 12.2.	Sample log file	196
Figure 12.3.	The knowledge discovery process	196
Figure 12.4.	Aggregated test-taking processes of students on Item 9 and Item 11 (directed graph).....	199
Figure 12.5.	Example of a MicroDYN item	200
Figure 12.6.	Aggregated problem solving behaviour on seven tasks, activities in the first three executions	201
Figure 12.7.	Job search task in PIAAC pre-test study	205

Figure 12.8.	Decision tree for the job search task	205
Figure 12.9.	Decision tree for a complex problem-solving task.....	206
Figure 13.1.	Screenshot of a scenario introduction	217
Figure 13.2.	The interface for drawing computer-based causal diagrams	218
Figure 13.3.	The first BioSphere scenario consists of two exogenous and three endogenous variables	219
Figure 14.1.	Framework for collaborative problem solving	230
Figure 14.2.	Illustration of an assessment task and of a stimulus-response-to-code structure.....	234
Figure 14.3.	Symmetric task: “Laughing Clowns”	235
Figure 14.4.	Asymmetric task: “Olive Oil”	236
Figure 14.5.	Example item characteristic curve observed (dotted line) and modelled (solid line)	239
Figure 14.6.	Differential item functioning for Student A and Student B – Typical solution.....	239

Tables

Table 2.1	Results of expert rating of PISA 2003 test items	38
Table 2.2	Intraclass correlation and relations with external variables for the three-dimensional model of analytical problem-solving competence: Mean differences and correlations	39
Table 3.1	The four possible outcomes of decisions based upon the controllability of a situation.....	53
Table 6.1	State transition matrix of a fictitious finite state automaton	100
Table 8.1	Goodness of fit indices for testing dimensionality of the dynamic problem solving model	131
Table 8.2	Goodness of fit indices for measurement invariance of DPS in the MicroDYN approach	131
Table 9.1.	Proposed task characteristics affecting item difficulty	144
Table 9.2	Ratings for MP3 Player Item 2 and Birthday Party Item 1	150
Table 9.3.	Standardised regression coefficients	152
Table 9.4.	Rotated component matrix	154
Table 10.1.	Sample characteristics of the Genetics Lab studies	161
Table 10.2.	Means, standard deviations, reliability and intercorrelations of the Genetics Lab’s performance scores	170
Table 11.1.	A possible partial credit framework for scoring an indicator describing the quality of exploration	183
Table 11.2.	Example of a tuneable scoring rule for the “time to first action” indicator	185
Table 12.1.	Process measures to cluster students	202
Table 12.2.	Clustering test takers based on problem-solving behaviour in an online environment.....	202
Table 12.3.	Process measures describing test takers’ activities for MicroDYN items	203
Table 12.4.	Clustering students based on online behaviour on the MicroDYN item.....	203

Table 13.1.	Information processing and interaction with the system	215
Table 14.1.	Components, strand elements and indicative behaviour needed for collaborative problem solving	231
Table 14.2.	Correlation matrices for Student A and Student B across the social and cognitive strands and their components	240