

Chapter 2

A Framework for Teachable Collaborative Problem Solving Skills

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Abstract In his book “Cognition in the Wild”, Hutchins (1995) invites his readers to scan their immediate environment for objects that were not produced through collaborative efforts of several people, and remarks that the only object in his personal environment that passed this test was a small pebble on his desk. In fact, it is remarkable how our daily lives are shaped by collaboration. Whether it is in schools, at the workplace, or in our free time, we are constantly embedded in environments that require us to make use of social skills in order to coordinate with other people. Given the pervasiveness of collaboration in everyday life, it is somewhat surprising that the development of social and collaborative skills is largely regarded as something that will occur naturally and does not require any further facilitation. In fact, groups often fail to make use of their potential (Schulz-Hardt, Brodbeck, Group performance and leadership. In: Hewstone M, Stroebe W, Jonas K (eds) Introduction to social psychology: a European perspective, 4th edn, pp 264–289. Blackwell, Oxford, 2008) and people differ in the extent to which they are capable of collaborating efficiently with others. Therefore, there is a growing awareness that collaborative skills require dedicated teaching efforts (Schoenfeld, Looking toward the 21st century: challenges of educational theory and practice. *Edu Res* 28:4–14, 1999). Collaborative problem solving has been identified as a particularly promising task that draws upon various social and cognitive skills, and that can be analysed in classroom environments where skills are both measurable and teachable.

This chapter provides a conceptual framework of collaborative problem solving that is informed by findings from fields of research as diverse as cognitive science, education, social psychology and psycholinguistics.

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Collaborative Problem Solving

Before defining collaborative problem solving, it might be helpful to define the constituents of this term, beginning with “collaboration” and followed by “problem solving”.

We define collaboration as the activity of working together towards a common goal. There are a number of elements included in the definition. The first element is **communication**, the exchange of knowledge or opinions to optimise understanding by a recipient. This element is a necessary but not sufficient condition for collaborative problem solving – it requires that communication goes beyond mere exchange. The second element is **cooperation**, which is primarily an agreed division of labour. Cooperation in collaborative problem solving involves nuanced, responsive contributions to planning and problem analysis. An alternative view might regard cooperation simply as a lower order version of collaboration, rather than as a component within it. Our reasons for not adopting this view are provided below. A third element is **responsiveness**, implying active and insightful participation.

From this definition, collaborative problem solving means approaching a problem responsively by working together and exchanging ideas. Collaboration is a useful tool, especially when specific expertise is needed (and available), and relies on factors such as a readiness to participate, mutual understanding, and the ability to manage interpersonal conflicts. Collaborative problem solving is particularly useful when dealing with problems that are complex.

In the learning sciences there was a major shift in the 1990s to move from “cooperative learning” towards “collaborative learning”. While many authors use these terms interchangeably, a key difference was identified by Dillenbourg and colleagues (1996). According to their distinction, cooperation is referred to as an activity which is accomplished through division of labour. In other words, while cooperative learners might coordinate at some points of their activity, they often work in parallel. Many scholars have noted that cooperative learning neither makes full use of a group’s potential nor requires the whole set of social skills that people rely on when working together (e.g. Cohen 1994). This led to focus on collaborative learning.

In collaborative learning, learners jointly orchestrate their activities in order to address a particular task or problem. The activities from learners are inextricably intertwined, contributions by learners mutually build upon each other, and one learner’s actions might be taken up or completed by another. Only when a task requires collaboration does the full set of social skills come into force. This makes tasks like collaborative problem solving some of the key testbeds for the assessment of 21st century skills.

Problem solving is an activity in which a learner perceives a discrepancy between a current state and a desired goal state, recognises that this discrepancy does not have an obvious or routine solution, and subsequently tries to act upon the given situation in order to achieve that goal state. It is accompanied by a number of mental and behavioural processes that might not necessarily take place in sequential order, but can run in parallel. One approach to conceptualising this notion has been taken

by the PISA group in their problem solving framework. First, a problem – that is, a discrepancy between current state and goal state – is identified. Second, a learner makes a mental representation of the problem states and of the steps that allow for a transformation between problem states (typically called a “problem space”). Third, a learner formulates a plan for steps that might enable a move nearer to the goal state. Fourth, the plan is executed. And fifth, the progress towards a problem solution is monitored.

Another, procedural approach implies a solution focus and an awareness of the nature of the problem and the goal states. Griffin (2014) argued that problem solving could be seen as a hierarchical series of steps moving from inductive to deductive thinking. The problem solver first examines the problem space to identify elements of the space. Next they recognise patterns and relationships between the elements, and formulate these into rules. The rules are then generalised and when generalisations are tested for alternative outcomes the problem solver is said to be testing hypotheses. This approach is elucidated in a later section of this chapter.

Based on these definitions and approaches, collaborative problem solving can be defined as a joint activity where dyads or small groups execute a number of steps in order to transform a current state into a desired goal state. The difference between individual and collaborative problem solving is that in collaboration each of these steps is directly observable. Participants need to exchange and share their identification of parts of the problem, their interpretation of the connections between the parts, relationships between action and effect (rules) and the generalisations they propose in search of a solution. The steps towards a collaborative solution may be coordinated through the use of verbal and non-verbal observable signals. Externalisation also has the welcome side effect of making problem solving activities visible and easier to assess.

The stages of individual problem solving apply – though in an altered and more complex fashion – to collaborative problem solving. The implications for the process of involving more than one problem solver in a collaborative context are discussed below.

Collaborative Problem Solving Processes

An idealised depiction of collaborative problem solving could follow a PISA-like sequential process. Collaborative problem solving requires that the collaborating parties recognise a problem and identify which elements of the problem space they can each control or monitor. Usually, each group member identifies a problem space and elements of that space, and additionally informs collaborators about the discrepancy between current and desired problem states (Larson and Christensen 1993).

Successful collaborative problem solving activities presuppose some kind of representation that is shared among participants. Research on so-called shared

mental models has shown that teams demonstrate better problem solving performances if the individual problem representations (the individual mental models of the problem) are similar among group members (Klimoski and Mohammed 1994). Similarity among representations can be achieved through communication. In contrast to a shared mental model approach that just looks at similarities among individual representations, Roschelle and Teasley (1995) have proposed the concept of a joint problem space. This problem space is created and maintained through constant coordination and communication among collaborators, and serves as a basis for collaborative action.

Collaborators need a shared plan on how to achieve a goal state. Collaborative planning needs to include the management of resources. Research on transactive memory systems (Wegner 1986) has shown that groups benefit if members know who knows what or who has identified specific elements of the problem space in a group. In the case of groups composed of members with different problem-relevant knowledge (i.e., consistent with the requisite features of problems that might justify collaboration), the management of resources ideally takes into account that group members share all available information. The occurrence of information sharing is far from guaranteed: social psychological research has demonstrated that group members tend to mention shared information but neglect unshared information that is unique to only one group member (Stasser and Titus 1985). Resource allocation is not limited to knowledge. It also needs to include the identification of capacity to perform processing and the monitoring of processes.

Plans must be executed by the group. In some collaborative problem solving situations this requires an orchestrated effort by several group members in parallel. One of the pitfalls of collaborative action is that groups typically suffer from process losses (Steiner 1972), i.e., groups perform worse than they ideally could, given the members' abilities and resources. Process losses can be caused by group members' reduced task motivation (social loafing; Karau and Williams 1993), by additional social goals resulting from the group situation that are taking away resources from the task (Wittenbaum et al. 2004), and by reduced cognitive capacity due to the social situation (Diehl and Stroebe 1987).

Progress and courses of action must be evaluated, plans must be reformulated if necessary, and collaborators must decide on how to proceed. This again involves the risk of process losses. The analysis of monitoring activities can be informed by research on how groups implicitly and explicitly orchestrate decision making. For instance, groups can be characterised through their use of implicit social decision schemes like "truth wins", "majority wins", or "plurality wins" (Laughlin and Ellis 1986). Moreover, groups can be differentiated by their explicit timing of decision making procedures. While some groups start by making decisions and then seek evidence that supports their decisions, other groups demonstrate a deliberative approach that starts with the seeking of evidence and then converges on a decision (Hastie and Pennington 1991). More generally, the successful allocation of resources requires awareness of a group's progress concerning the problem it faces and the resources available within the group, and is facilitated by a shared understanding of the desired state (Peterson and Behfar 2005).

In this logical sequence of processes, participants externalise their individual problem solving processes, and coordinate these contributions into a coherent sequence of events. The degree to which this idealised sequence takes place in reality is unclear. In any given case, its occurrence will be dependent not only on the groups' dynamics but on the characteristics of the problem space.

Collaborative problem solving is not a uniform process but a complex, coordinated activity between two or more individuals. Consequently, efficient problem solving does not rely on a uniform skill but rather a set of distinguishable sub-skills which are deployed in accordance with situational needs. While the five processes mentioned above (problem identification, problem representation, planning, executing, monitoring) can serve to describe collaborative problem solving, it is not the case that collaborative problem solving *skills* can be easily mapped to the different stages. Rather, many skills cut across several problem solving stages.

Collaborative Problem Solving Skills

Based on the literature in several research fields, the ATC21S™ project¹ has developed a framework consisting of a hierarchy of skills that play a pivotal role in collaborative problem solving. The identified skills must fulfill three criteria: (1) they must be measurable in large-scale assessment, (2) they must allow the derivation of behavioural indicators that (after some training) can be assessed by teachers in a classroom setting, and (3) they must be teachable. Only if these three conditions are met will collaborative problem solving skills become a part of learning diagnostics, both in everyday classroom practice and in large-scale assessment studies like PISA (OECD 1999).

The framework of collaborative problem solving skills proposed here is based on the distinction between two very broad skill classes: social skills and cognitive skills. Social skills constitute the “collaborative” part of “collaborative problem solving”. They play an important role in collaborative problem solving but are also a feature of many other collaborative tasks. Cognitive skills constitute the “problem solving” part of “collaborative problem solving”. These skills address typical cognitive issues of problem solving and have more in common with classical approaches to individual problem solving. To clarify this distinction it can be said that the social skills are about managing participants (including oneself), whereas cognitive skills are about managing the task at hand. In the following, both classes of skill are described and discussed in more detail.

¹ The acronym ATC21S™ has been globally trademarked. For purposes of simplicity the acronym is presented throughout the chapter as ATC21S.

Social Process Skills

In order to be successful in collaborative problem solving, individuals need a number of social skills to help them coordinate actions in synchrony with other participants. Our conceptualisation of social skills refers in particular to three classes of indicators that can be subsumed under the general rubric of social skills: participation, perspective taking, and social regulation (Table 2.1). Participation describes the minimum requirements for collaborative interaction. It refers to the willingness and readiness of individuals to externalise and share information and thoughts, and to be involved in the stages of problem solving (Stasser and Vaughan 1996). The concept of perspective taking skills refers to the ability to see a problem through the eyes of a collaborator (Higgins 1981). This can be extremely helpful, as it allows for smoother coordination among collaborators. Moreover, for particular types of tasks, perspective taking skills are essential, as a group cannot come to a solution unless its members have the capacity to understand the concrete situation their collaborators are in (e.g., Trötschel et al. 2011). Finally, the concept of social regulation skills refers to the more strategic aspects of collaborative problem solving (Peterson and Behfar 2005). Ideally, collaborators use their awareness of the strengths and weaknesses of all group members, to coordinate and resolve potential differences in viewpoints, interests and strategies.

Participation Skills

Many accounts in the learning sciences stress the importance of participation, albeit with slightly different focuses. According to socio-constructivist epistemologies, participation refers to the long-term process of becoming part of a community of practice (Lave and Wenger 1991). At first, learners take a peripheral role in a community (legitimate peripheral participation), but once they become more experienced as community members they take on more responsibilities. According to a cognitively and linguistically oriented epistemology, participation refers to the observable action of engaging in discourse. In this research tradition, Cohen (1994) suggested that the extent to which learners participate in a collaborative activity is the best predictor of individual learning outcomes, provided that a task is collaborative (i.e. it cannot be accomplished by division of labour alone) and provided that the problem is relatively ill-structured. Whichever epistemology is preferred, participation is regarded as a crucial concept in the learning sciences that constitutes or at least leads to learning.

Within the range of participation skills, our framework further distinguishes between three aspects: action, interaction, and task completion. “Action” refers to the general level of participation of an individual, irrespective of whether this action is in any way coordinated with the efforts of other group members. While most classical psychologists would argue that actions are just behavioural consequences of internal, cognitive processes, many learning scientists regard actions as the fundamental “carriers” of cognition (Hutchins 1995; Nardi 1996). Problem solvers

Table 2.1 Social skills in collaborative problem solving

Element	Indicator	Low	Middle	High
Participation				
Action	Activity within environment	No or very little activity	Activity in familiar contexts	Activity in familiar and unfamiliar contexts
Interaction	Interacting with, prompting and responding to the contributions of others	Acknowledges communication directly or indirectly	Responds to cues in communication	Initiates and promotes interaction or activity
Task completion/perseverance	Undertaking and completing a task or part of a task individually	Maintains presence only	Identifies and attempts the task	Perseveres in task as indicated by repeated attempts or multiple strategies
Perspective taking				
Adaptive responsiveness	Ignoring, accepting or adapting contributions of others	Contributions or prompts from others are taken into account	Contributions or prompts of others are adapted and incorporated	Contributions or prompts of others are used to suggest possible solution paths
Audience awareness (Mutual modelling)	Awareness of how to adapt behaviour to increase suitability for others	Contributions are not tailored to participants	Contributions are modified for recipient understanding in the light of deliberate feedback	Contributions are tailored to recipients based on interpretation of recipients' understanding
Social regulation				
Negotiation	Achieving a resolution or reaching compromise	Comments on differences	Attempts to reach a common understanding	Achieves resolution of differences
Self evaluation (Metamemory)	Recognising own strengths and weaknesses	Notes own performance	Comments on own performance in terms of appropriateness or adequacy	Infers a level of capability based on own performance
Transactive memory	Recognising strengths and weaknesses of others	Notes performance of others	Comments on performance of others in terms of appropriateness or adequacy	Comments on expertise available based on performance history
Responsibility initiative	Assuming responsibility for ensuring parts of task are completed by the group	Undertakes activities largely independently of others	Completes activities and reports to others	Assumes group responsibility as indicated by use of first person plural

differ in the level of sophistication with which they act in a group. While some problem solvers do not become active at all, others become active once the environment is highly scaffolded (e.g. through explicit task instructions). Finally, the most sophisticated way of acting in a group is demonstrated by those who have the ability to perform actions even in the absence of instructional scaffolds.

“Interaction” refers to behaviour that demonstrates interaction with and responses to others. For instance, some learners are highly active in collaborative problem solving, but fail to respond to or coordinate with their collaborators. A higher level of interaction skill is exemplified by problem solvers who respond to cued interaction, e.g. by answering an inquiry from a collaborator. The highest level of interaction skill manifests itself if learners actively initiate coordination efforts, or prompt their collaborators to respond. Interaction among problem solvers is a minimum requirement for successful coordination (Crowston et al. 2006) and it is achieved through verbal and nonverbal means (Clark 1996).

“Task completion” skills refer to motivational aspects of participation and consequent perseverance on a task. Collaborative problem solvers differ in the degree to which they feel committed to the activity. Accordingly, they may enter the problem solving space but not be sufficiently engaged to remain actively involved, or at the other end of the spectrum, may persist in engagement as indicated by multiple attempts at tasks or by trying different strategies.

Perspective Taking Skills

While the quantity of participation is an important predictor of collaborative problem solving performance, perspective taking skills revolve more around the quality of interaction. Theoretically, perspective taking can be linked to constructs that stem from sub-disciplines as diverse as psychology of emotion, social psychology, and psycholinguistics, and consequently perspective taking encompasses affective, social-developmental, and linguistic aspects. Perspective taking is a multidimensional construct. On an affective level, perspective taking can be linked to the notion of empathy and the emotional understanding of, and identification with, others. More important in the current context, on a cognitive level, perspective taking is related to “theory of mind” concepts, and it describes the ability to understand a state of affairs from a different spatial or psychological perspective. If this ability is not in place, people are subject to egocentric bias, i.e. they expect others to be highly similar to themselves (Zuckerman et al. 1983). Perspective taking is often considered a core communicative competence (Weinstein 1969). Finally, a linguistic aspect of perspective taking refers to the ability to contextualise utterances of peers by reference to background information, but also the ability to tailor one’s own utterances to the needs and intellectual capabilities of peer learners. This ability is often subsumed under the label of ‘audience design’ (Clark and Murphy 1982). It should be noted that while there is a general consensus among scholars that audience design is helpful to coordinate mutual activities, empirical evidence indicates that participants sometimes lack the ability or willingness to adapt to their communication partners (e.g. Horton and Keysar 1996).

The framework of collaborative problem solving skills distinguishes between two aspects of perspective taking skills: responding skills and audience awareness skills. Responding skills become apparent when problem solvers manage to integrate contributions of collaborators into their own thoughts and actions. For instance, problem solvers who rethink a problem representation based on evidence that was reported by a collaborator exhibit a high degree of responding skill. In contrast, ignoring contributions from others exemplifies a low degree of responding skill.

Audience awareness skills are constituted by the ability to tailor one's contributions to others (Dehler et al. 2011). Depending on variables like the amount of egocentric bias, problem solvers are more or less skilled in adapting their utterances to the viewpoints of others, or to making their actions visible and comprehensible to their collaborators. For example, imagine two problem solvers who are placed on different sides of a transparent screen. For a particular object on the left side from a problem solver's point of view, low audience awareness would be exhibited by referring to the object as being "on the left side". In contrast, higher audience awareness would be exemplified by referring to the object as being "on the right side" or even "on your right side".

To clarify the distinction between responding skills and audience awareness skills it can be said that the former involve the ability to be adaptive in one's internalisations of information (similar to Piaget's accommodation; Piaget and Inhelder 1962), whereas the latter involve the ability to be adaptive in one's externalisations of knowledge. The two aspects of perspective taking explicated in the current framework can thus be characterised respectively as *receptive* and *expressive*.

Social Regulation Skills

One of the main benefits of collaborating in a group is the potential diversity group members bring to their interactions. Different members have different knowledge, different expertise, different opinions, and different strategies. Evidence for the power of diversity has been found in the research of various disciplines that analyse group performance. For instance, in organisational psychology the concept of informational diversity among team members was identified as a key ingredient of team performance (De Wit and Greer 2008). The effects of diversity are particularly positive when group tasks require creativity and elaboration (van Knippenberg and Schippers 2007). In education, diversity among group members is considered to stimulate useful cognitive conflict (Doise and Mugny 1984), conceptual change (Roschelle 1992), or multiperspectivity (Salomon 1993). However, diversity per se is not in itself valuable and only becomes useful in collaboration when participants know how to deal with the diversity of viewpoints, concepts, and strategies under discussion (van Knippenberg et al. 2004). In other words, collaborative problem solvers need strategic skills to harness the diversity of group members, and they must employ mechanisms of social regulation and negotiation (Thompson et al. 2010) that act appropriately on group diversity. Groups have a tendency not to make use of the full potential of diversity (Hinsz et al. 1997). Among other things, dissenting information is often disregarded by individuals (confirmation bias; Jonas et al.

2001), shared information is preferred over unshared information (Stasser and Titus 1985), and minority viewpoints have less influence than majority viewpoints (Wood et al. 1994). If group members possess the skills to overcome biased information handling in groups and can regulate conflicts, they can fully exploit the benefits of diversity that their collaborators bring into the joint problem solving effort.

The framework of collaborative problem solving skills distinguishes four aspects that can be related to social regulation: metamemory, transactive memory, negotiation and initiative. The first two of these aspects refer to the ability to recognise group diversity, which breaks down into knowledge about oneself (metamemory; Flavell 1976), and knowledge about the knowledge, strengths, and weaknesses of one's collaborators (transactive memory; Wegner 1986). If these two skills are employed, collaborative problem solving groups will lay the groundwork to harness the power of group diversity.

The presence or absence of negotiation skills becomes apparent when conflicts arise among group members. These may be conflicts about how to represent a problem, about potential solution steps, about how to interpret evidence that is available to the group, or about the group's goals. In any of these cases, problem solvers must negotiate the steps and measures that accommodate the differences between individual approaches, for example by formulating compromises or by determining rank orders among alternative solution steps.

Finally, the term initiative skills refers to the responsibility that a problem solver experiences for the progress of the group. If this collective responsibility (Scardamalia 2002) is too low, lurking behaviour or disengagement from the task becomes likely, and it could be that the collaborative task becomes unsolvable. In contrast, higher responsibility is likely to contribute to better problem solving performance. While some problem solvers shun confrontation or even interaction by focusing on their individual solution attempts, others will take responsibility for working on a shared problem representation, developing a strategic plan towards a solution, and regularly monitoring activities on the group's progress.

If these different skills of social regulation are apparent in a group, the coordination of collaborative problem solving activities becomes much easier, and the potential diversity among group members will be exploited in highly beneficial ways.

Cognitive Process Skills

The effectiveness and efficiency of collaborative problem solving relies not only on social skills but also on cognitive skills. Cognitive skills of collaborative problem solving are highly similar to those skills that are conducive to individual problem solving, and they refer to the ways in which problem solvers manage the task at hand and the reasoning skills employed. The framework of collaborative problem solving categorises cognitive skills across planning, executing and monitoring, flexibility, and learning. Planning skills consist in an individual's capability to develop strategies based on plausible steps towards a problem solution (Miller et al. 1960).

In the case of collaborative problem solving, plans need to address a shared problem representation and provide the basis for an orchestrated and well coordinated problem solution (Weldon and Weingart 1993). While planning refers to prospective actions like building hypotheses, executing and monitoring is of a more retrospective nature. Problem solvers must interpret evidence, and must reflect on the appropriateness of planned and executed solution steps (Peterson and Behfar 2005). Monitoring is considered here as an individual-level skill, because it is more effective when it is done individually and externalised afterwards than when learners reflect jointly about the group process (Gurtner et al. 2007). This serves as a basis for the continuing adjustment of plans, thereby setting in motion a cyclical problem solving behaviour. Flexibility skills are demonstrated in the creativity that problem solvers exhibit when facing a particularly challenging part of a problem solution (Star and Rittle-Johnson 2008), but also include the way problem solvers react to ambiguous situations. These are particularly important if the problems are ill-defined and require some sort of inductive thinking. Finally, learning skills are demonstrated in the ability to learn during group interaction or as a consequence of group interaction. They lead to knowledge building. These four cognitive skill classes are elaborated in Table 2.2.

Table 2.2 Cognitive skills in collaborative problem solving

Element	Indicator	Low 0	Middle 1	High 2
Task regulation				
Organises (problem analysis)	Analyses and describes a problem in familiar language	Problem is stated as presented	Problem is divided into subtasks	Identifies necessary sequence of subtasks
Sets goals	Sets a clear goal for a task	Sets general goal such as task completion	Sets goals for subtasks	Sets goals that recognise relationships between subtasks
Resource management	Manages resources or people to complete a task	Uses/Identifies resources (or directs people) without consultation	Allocates people or resources to a task	Suggests that people or resources be used
Flexibility and ambiguity	Accepts ambiguous situations	Inaction in ambiguous situations	Notes ambiguity and suggests options	Explores options
Collects elements of information	Explores and understands elements of the task	Identifies the need for information related to immediate activity	Identifies the nature of the information needed for immediate activity	Identifies need for information related to current, alternative, and future activity

(continued)

Table 2.2 (continued)

Element	Indicator	Low 0	Middle 1	High 2
Systematicity	Implements possible solutions to a problem and monitors progress	Trial and error actions	Purposeful sequence of actions	Systematically exhausts possible solutions
Learning and knowledge building				
Relationships (Represents and formulates)	Identifies connections and patterns between and among elements of knowledge	Focused on isolated pieces of information	Links elements of information	Formulates patterns among multiple pieces of information
Rules: “If ... then”	Uses understanding of cause and effect to develop a plan	Activity is undertaken with little or no understanding of consequence of action	Identifies short sequences of cause and effect	Uses understanding of cause and effect to plan or execute a sequence of actions Plans a strategy based on a generalised understanding of cause and effect
Hypothesis “what if...” (Reflects and monitors)	Adapts reasoning or course of action as information or circumstances change	Maintains a single line of approach	Tries additional options in light of new information or lack of progress	Reconstructs and reorganises understanding of the problem in search of new solutions

Task Regulation Skills

“Planning” is one of the core activities of problem solving (Gunzelmann and Anderson 2003). On the basis of a (joint) problem space, planning involves the formulation of hypotheses concerning how to reach the goal, and the selection of steps that move the problem-solving process forward. Planning is a crucial meta-cognitive activity, as it requires problem solvers to reflect on their own (and others’) cognitive processes (Hayes-Roth and Hayes-Roth 1979). We distinguish between four aspects of planning: problem analysis, goal setting, resource management and complexity. Planning begins with a *problem analysis*, an inspection of the individual or joint representation of a problem through which the task is segmented into sub-tasks with consequent sub-goals. Sub-tasks and sub-goals can not only make the problem solving process more tractable, they can also serve as important yardsticks to evaluate one’s progress (i.e., monitoring). A good problem solver is able to *formulate specific goals* (“Next, we must move this block one tile to the left”),

whereas lower sophistication is exhibited by formulating no goals or very vague ones (“We must try our best to change those blocks”). Research on teamwork has shown that goal specificity improves a group’s performance (Weldon and Weingart 1993). The more a problem solver is inclined to set specific goals, the easier it is to assess and ultimately achieve them. Many collaborative problem solving tasks can only be accomplished if available resources are distributed properly. Resource management reflects the ability to plan how collaborators can bring their resources, their knowledge, or their expertise into the problem solving process. A low level of resource management skills is evident if a problem solver only plans with those resources that are available to herself. Suggesting that collaborators make use of specific resources indicates better resource management skills, whereas the highest skill level is exhibited when problem solvers explicitly decide on allocation of resources to people and/or task components. Therefore, an important aspect of planning is to *manage resources* that are available to oneself and to one’s collaborators (Brown 1987). Finally, plans can differ in *complexity* or sophistication. This can best be described by reference to a chess match. If a piece is moved without prior reflection, planning complexity is low. If a sequence of moves is planned, and if potential counter moves are reflected in parallel plans of alternative routes, higher complexity in planning skill is demonstrated. To address these issues the framework of collaborative problem solving skills introduces the skill class of fluidity problems, which breaks down into two aspects: tolerance for ambiguity, and breadth. Different levels of ambiguity tolerance lead to different problem solving behaviours – some problem solvers become active only in unambiguous situations, some react to ambiguity by exploring the problem space, while problem solvers with high levels of ambiguity tolerance are likely to interpret ambiguous situations in a way that helps them in their decision making about the next solution step. As to breadth, a low skill level is displayed if problem solvers follow only a single approach of inquiry. A medium level of flexibility entails trying multiple approaches once an impasse is reached, or once new evidence is available via monitoring. And a high level of breadth leads to a re-organisation of problem representation or planning activities if progress through the problem space is impeded.

Problem solving is an activity that requires participants to cope with various barriers. For instance, most problems are inherently ambiguous because the best possible solution step is not always easily identifiable. Moreover, solution steps might lead to an impasse which represents a failure of the effort as it was originally planned. It is not uncommon for problem solvers to withdraw from a problem when they perceive roadblocks along the way to a solution. This can happen with all kinds of problems but it becomes particularly important for ill-defined problems that are ambiguous by definition. Tolerance for ambiguity (Norton 1975) is a characteristic of problem solvers that can help to overcome the barriers in problem solving activities. Moreover, good problem solvers are adept at changing plans in a flexible manner.

Research on human and machine problem solving has identified a number of recurring strategies that describe different approaches on how to tackle a problem.

For instance, one approach was termed ‘forward search’ (Newell and Simon 1972), and it can be characterised by taking a current problem state and identifying the most promising operator or move, thereby working towards the goal state. Variants of forward search include a breadth-first search (sequentially checking potential next moves) and depth-first search (following the most promising move until an impasse is reached). ‘Backward search’ through a problem space is the counterpart to forward search, and it starts with identifying the most likely or promising antecedent of a goal state, thereby working backwards through problem space. Backward search and forward search have been combined by Newell and Simon (1972), who have developed a means-ends-analysis based on the idea of selecting actions that minimise the difference between current state and goal state. This means-ends-analysis effectively comprises both forward search and backward search. However, while this and similar techniques can help to describe well-defined problems formally, they do not fully capture the complexity of ill-defined problems. For instance, many real-world problems are “wicked” because problem solvers lack necessary information (Van Gundy 1987). Realising that some crucial information is missing, and developing strategies on how to acquire this information, are important monitoring activities. In collaborative problem solving, this type of monitoring becomes essential, as different problem solvers typically have access to different types of information or have different means to access needed information (Larson and Christensen 1993).

Consequently, the framework of collaborative problem solving skills distinguishes between two “executing and monitoring” processes: information collection and systematicity. Information collection skill refers to the ability to identify what information is required and how and when it can be acquired. Some problem solvers lack the skills to identify the types of information required. Others will recognise the nature of the information needed, but only with regard to the current activity or problem state. Finally, a high level of these skills entails assessing the need for information with regard to current, alternative, and future problem states. Systematicity refers to the level of sophistication that a problem solver’s strategy exhibits. The most basic level of systematicity involves problem solving as a trial and error process. A medium level of systematicity is indicated by the use of forward search through a problem; whereas high systematicity can be identified when forward and backward search are combined through means-ends-analysis or similar techniques, followed by highly reflective monitoring activities.

Learning and Knowledge Building Skills

Brodbeck and Greitemeyer (2000) have characterised learning as a by-product of collaborative problem solving. Through progress in a collaborative problem solving task, individuals can learn about a content domain or about strategies and skills; they can also learn how to deal with impasses or how to coordinate, collaborate and negotiate with others. There are different ways to conceptualise learning, and the corresponding epistemologies for two of these have been described as participation

and acquisition metaphors (Sfard 1998). The classical acquisition metaphor regards learning as the accumulation or restructuring of individual mental representations that leave measurable residues after a task is completed. In this case, the amount of learning can be measured through knowledge tests. In contrast, the participation metaphor is heavily influenced by situated cognition (Greeno 1998) and socio-culturalism (Vygotsky 1978), and regards learning as an activity rather than an outcome. The role of mental representations is downplayed and, according to this epistemology, knowledge is rather to be found in the environment (the task, the discourse, the artifact) than in the heads of learners. A particular view of learning that can be subsumed under the participation metaphor is knowledge building (Scardamalia 2002). According to this view, learning is a discursive process through which collaborators generate a network of ideas that build on each other. While the knowledge building epistemology seeks for learning during the process of collaborative problem solving, the acquisition metaphor of learning would assess learning through the transfer of skills or understandings.

The framework of collaborative problem solving skills touches on both these aspects, characterising the two as *knowledge building* and *learning*. Knowledge building is exemplified by the ability to take up ideas from collaborators to refine problem representations, plans, and monitoring activities. The highest level of knowledge building occurs in those problem solvers who are able to integrate and synthesise the input from collaborators (Scardamalia 2002) in the description and interpretation of a given problem. Learning is indicated by the ability to identify and represent relationships, understand cause and effect, and develop hypotheses based on generalisations. A low level of learning skills would be evident if the only knowledge that is extracted from a problem solving activity stems from information that was directly provided through instruction.

Griffin (2014) proposed a hierarchy of steps in problem solving which lead to knowledge building. At an initial level (beyond random guessing), students rely on identifying isolated elements of information. In a collaborative setting where information is unevenly and asynchronously distributed, these elements need to be shared. Problem solvers generally describe relationships or connections between elements of information (data) and make observations that form patterns, lending meaning to the problem space. At the next level of problem analysis, systematic observations of *cause and effect* enable players to formulate and discuss the potential of rules, either for the regulation of the task or for the manner of collaboration. At a more sophisticated level, rules are used to complete steps or parts of the problem solution. For the most difficult sub-tasks, more able students demonstrate an ability to generalise to a range of situations by setting and testing *hypotheses*, using a “What if...?” approach. An ordered progression, moving through pattern, rule and generalisation to hypothesis, can be developed by the collaborating partners and alternative solution options can be proposed and tested.

It is clear that there are overlapping cycles of cognitive processes across the general skill areas of task regulation – which includes planning, executing and monitoring, and comprehending complexity – and of knowledge building and learning. The essential difference between the two general areas consists in the use made by task

regulation processes of the scoping of the problem space and the collection of information, which contrasts with the use of this information for extrapolation purposes in knowledge building and learning. For all the elements of the collaborative problem solving framework, the notions of teachability and learnability have been central to their conceptualisation. The rubrics in Table 2.2 give expression to the central place of this notion/these notions, and provide nutshell glimpses of the implications of the theoretical underpinnings of the construct for implementation in an assessment framework.

The debt of the presented framework to the work of Polya (1973), Mayer (1983), and the OECD PISA problem solving framework is substantial. The potential tension between a process approach to problem solving and a cognitive ability approach is evident in the long history concerning teachability of higher-order thinking processes. The ATC21S position, taking into account its assessment and teaching endeavour, is that the function of assessment is primarily to provide data to inform teaching. Consequently a process approach to collaborative problem solving is consistent with the project's primary goals. The extent to which individuals can be taught how to solve problems collaboratively is still unknown. It is clear that the distinct classes of sub-skills outlined in the framework can be taught. What is not so clear is whether an individual can be taught to draw on those sub-skills appropriately. It is at this point that the distinction between the process approach and a cognitive approach becomes the point of tension, and the focus for future research.

Assessment of Collaborative Problem Solving Skills

In order to assess problem solving skills in educational contexts, we must think about tasks that address the various skill classes described above. One of the decisions involved in identifying tasks relates to a trade-off between task realism and measurability. As to realism, collaborative problem solving can be found in many everyday activities: sitting together with a colleague and trying to format a software object; jointly developing a policy for student cafeteria use that takes into account the interests of various stakeholders; identifying a movie that is in line with the taste of a group of friends – all these are examples in which a group must identify a non-obvious solution that requires shared understanding and negotiation among collaborators. What these tasks often have in common is that they are ill-defined. For instance, the desired goal state cannot be clearly described (e.g. agreeing on a good cafeteria policy; finding a suitable movie). Furthermore, problems can be ill-defined because individuals and groups are not fully aware of the repertoire of actions that can lead them from the current state towards a goal state.

While many problems in real life are collaborative and ill-defined, the vast majority of research on problem solving has dealt with well-defined problems that are presented to individuals. A typical example for a well-researched problem is the “Tower of Hanoi” where individuals move disks according to specified

rules in order to transform an original state into a well-defined goal state. Beginning with the seminal work by Newell and Simon (1972), an accumulation of research evidence has begun to show how individual problem solving behaviour can be understood and computationally modelled as the application of simple rules and heuristics. An advantage of these well-defined tasks is that their representational and computational dynamics are quite well understood. Consequently, there are agreed-upon standards for how to measure problem solving effectiveness.

The differences between real-world problems and problems as they are often analysed in psychological research raise the question of whether collaborative problem solving is best addressed by the use of well-defined or ill-defined tasks. Well-defined tasks allow for easier comparisons between different tasks and between different problem solvers, thereby providing the basis for the establishment of problem solving standards. Using well-defined tasks should also increase the teachability of collaborative problem solving, as the problem solving steps for well-defined tasks can be easily demonstrated, understood, adopted in the pursuit of alternative solution paths, or reflected upon. Therefore ATC21S has taken the approach that it is desirable for the design of collaborative problem solving tasks to begin with tasks that in some instances are designed for individual problem solving and transform these into collaborative tasks. For example, a typical approach to create collaborative (rather than cooperative) contexts is to introduce resource interdependence (Johnson et al. 1998). Modification of tasks can be implemented in this way to ensure that a task cannot be solved by any one individual working alone. The disadvantage of this approach is that it may not teach students to deal with truly ill-defined problems, since the constraints of the tasks are such that all resources are available, notwithstanding their lack of visibility.

Summary

With its wide applicability to real-life situations, collaborative problem solving – the joint and shared activity of transforming a current problem state into a desired goal state – can be regarded as one of the key skills in the 21st century. This chapter has proposed a framework that breaks down collaborative problem solving skills into a number of components. Most importantly, the social skills of collaboration can be distinguished from the cognitive skills of problem solving. Within these subgroups, certain skill aspects can be identified. The framework draws on research from several fields, and lays the ground for a deeper analysis of collaborative problem solving. One of the main purposes of this framework is to inform the design of collaborative problem solving tasks that touch on as many of the identified skill sets as possible. Once results from such tasks are available, testing of the theoretical hypotheses underlying the framework can take place in order to validate or refine the framework, thereby deepening our understanding of collaborative problem solving.

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