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Innovative Research-Based Approaches to Learning and Teaching

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INNOVATIVE RESEARCH-BASED APPROACHES TO LEARNING AND TEACHING

EDU Working paper 79

This paper has been prepared by Gesa S. E. van den Broek of the Behavioural Science Institute, Radboud University, Nijmegen, in the Netherlands. It provides background analysis for the Innovative Learning Environments (ILE) project, by synthesizing different approaches aimed at innovating learning based on insights from learning research. It explicitly builds on the summary provided in the earlier ILE publication Innovating to Learn, Learning to Innovate (OECD Publishing, 2008) by Marlene Scardamalia and Carl Bereiter in their chapter "Towards Research-based Innovation"(pp.67-91).

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SUMMARY

Building on an earlier 2008 summary prepared for OECD by Marlene Scardamalia and Carl Bereiter, this paper by Gesa S. E. van den Broek provides a more extensive discussion of approaches described as "research based innovation." *Fostering Communities of Learning* is a constructivist approach in which teachers help students discover important curricular concepts. *Learning by Design* is an inquiry-based science learning programme based on case-based reasoning models. *Central Conceptual Structures* (CCS) theory describes developmental changes in children's thinking and what is needed to progress through stages in specific cognitive domains. *Web-based Inquiry Science Environment* (WISE) is an internet-based adaptive learning environment building on the principles of knowledge integration. *Cognitive Tutors and ACT-R theory* are intelligent adaptive software programmes that provide students with scaffolded instruction and feedback. *Direct Instruction* aims to accelerate learning through clear scripted direct instruction by the teacher and scaffolded practice aimed at student involvement and error reduction. *Higher Order Thinking Skills* (HOTS) is for disadvantaged students especially to engage in Socratic dialogues about ideas and strategies to solve computer game-based problems. *Knowledge Building* is a constructivist teaching approach centred on building knowledge and creating knowledge communities.

RÉSUMÉ

S'inspirant d'une synthèse précédente rédigée par Marlene Scardamalia et Carl Bereiter pour l'OCDE en 2008, la présente note, de Gesa S. E. van den Broek, propose une réflexion plus large sur les approches relevant de ce que l'on appelle « l'innovation fondée sur la recherche ». *Encourager les communautés apprenantes* s'inscrit dans une démarche constructiviste selon laquelle les enseignants aident leurs élèves à découvrir des concepts importants du programme scolaire. *Learning by Design* est un programme d'apprentissage des sciences à partir d'enquêtes et de modèles de raisonnement fondés sur des études de cas. La théorie des *structures conceptuelles centrales* décrit l'évolution développementale du raisonnement des enfants et ce qui est nécessaire pour progresser et franchir des étapes dans des domaines cognitifs particuliers. WISE (*Web-based Inquiry Science Environment*) est un environnement pédagogique adaptatif sur internet qui repose sur les principes de l'intégration des connaissances. Les *tuteurs cognitifs et la théorie ACT-R* sont des logiciels adaptatifs intelligents qui proposent aux élèves une instruction et des retours d'information étayés. L'*instruction directe* vise à accélérer l'apprentissage grâce à des cours clairs, structurés et directs prodigués par l'enseignant, ainsi qu'à travers une application pratique et documentée favorisant la participation des élèves et la diminution des erreurs. Le programme HOTS (*Higher Order Thinking Skills*), destiné aux élèves de milieux défavorisés, a notamment pour objectif d'organiser des échanges d'idées et de stratégies en vue de résoudre des problèmes à partir de jeux électroniques. Le *renforcement des connaissances* est une approche pédagogique constructiviste axée sur le développement des connaissances et la création de communautés du savoir.

INNOVATIVE RESEARCH-BASED APPROACHES TO LEARNING AND TEACHING

Gesa Sonja Elsa van den Broek[1]

Scientific knowledge about effective learning, as identified in "*The Nature of Learning: Using Research to Inspire Practice"* (OECD, 2010) calls for substantial innovation and change in current educational practice. Learning must become more social, authentic, adapted to individual motivations and abilities, reflective, and strategic - to name just a few challenges. The purpose of *design research* is to enable such change, by inspiring, testing and refining innovative practice in the classroom.

Design research is theory-driven research that takes place in naturalistic contexts like real schools: Aspects of the environment are systematically manipulated based on cognitive models of learning and teaching, in order to observe which practice works best and to understand why and how instructional strategies and tools work (Barab, 2006). Ultimately, this is expected to lead to new, effective approaches to learning and teaching, based on scientific knowledge and have been tried out and refined in practice by students and teachers. This requires a close collaboration between researchers and teachers, repeated cycles of implementing, testing and refining practice, as well as careful and extensive observation and documentation (see Barab, 2006; Confrey, 2006).

Design research is still not nearly as common in education as in other disciplines like engineering (Bereiter & Scardamalia, 2008). However, it has already given rise to a number of promising new approaches to teaching and learning. A brief overview of important research-based approaches in education was provided by Bereiter and Scardamalia in an annex to their chapter in the OECD publication "Innovating to learn, learning to innovate" (OECD, 2008). The purpose of the present paper is to build on that overview in order to provide a more extensive discussion of the approaches listed.

The specific approaches discussed in the following are: Fostering Communities of Learning (Brown & Campione, 1994), Case based Reasoning and Learning by Design (Kolodner, 1992), Central Conceptual Structures Theory (Case & McKeough, 1989), Web-based Inquiry Science Learning (Linn, Clark, & Slotta, 2002), Cognitive Tutors (Koedinger & Corbett, 2006), Direct Instruction (Adams & Engelmann, 1996a), Higher Order Thinking Skills (Pogrow, 1987, 2004), and Knowledge Building (Scardamalia & Bereiter, 2006b). For each approach, the theoretical base and defining characteristics are discussed together with illustrations of concrete practice. The concluding section of this paper briefly summarizes the presented approaches in terms of three dimensions of innovative educational practice that were introduced by Scardamalia and Bereiter to distinguish among different socio-constructivist approaches to learning and teaching (2008).

Fostering Communities of Learning

Fostering Communities of Learners (FCL) is a constructivist teaching model that emphasizes democratic, student-centred, and inquiry-based instruction oriented toward the development of higher-order understanding by means of complex, authentic tasks, collaborative scientific research, and reciprocal teaching (Mintrop, 2004; Shulman & Sherin, 2004). FCL has its origins in the early 1990s, when Ann

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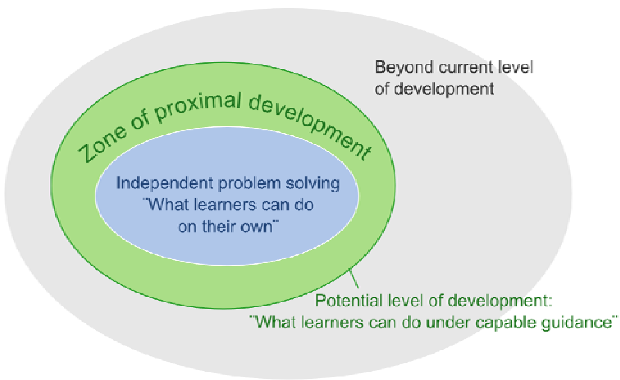
Brown and John Campione from Berkeley University devoted a research programme to the study of learning "in the blooming, buzzing confusion of inner-city classrooms" (Brown, 1992). This led to the development of FCL. Their starting point were principles of learning that were specific and clear enough to guide practice in such a way that pedagogical techniques could be adopted based on those principles, rather than just surface procedures (Brown, 1994). This work is often associated with the origin of modern design-based research in which educational innovations are iteratively tested and refined in real classrooms (Barab, 2006).

On the side of theory, FCL builds to an important extent on the Vygotskian notion of a zone of proximal development, as well as concepts by other authors that Brown and Campione (1994) refer to as "region of sensitivity to instruction", "readiness area", or "bandwidth of competence" (p. 230). In this context, the *zone of proximal development* is defined as the difference between what individual learners can do or understand on their own, and what they can achieve with the help of a more skilful peer or adult (see Figure 1). In other words, it refers to the distance between the level of learning that a child can reach independently, and the level that it can potentially reach under capable guidance. The aim of learning activities in the zone of proximal development is that the child learns to become independently proficient at tasks that it can initially only accomplish with help.

Figure 1. Graphical Illustration of the Zone of Proximal Development



The common conception of the zone of proximal development is "the distance between the actual developmental level as determined by independent problem solving and the level of potential development as determined under adult guidance or in collaboration with more capable peers" (Vygotsky, 1978/1935, p.86).

FCL emphasizes that the role of the teacher is to guide the students' discovery process towards the upper bounds of their zone of development (Brown, 1994). This is a demanding role because the teacher must guide the students' learning adventures with a good judgment of when to intervene and when to let students solve problems on their own. Therefore, teachers need to have a good sense of each student's zone of proximal development in order to direct the students toward forms of inquiry that they would not reach without help. Each teacher implements his or her version of FCL so that there is considerable variability in different classes.

However, several characteristics of successful classrooms must be operating for FCL to be judged in place (Brown & Campione, 1994). These essential characteristics of FCL classrooms are:

(1) Individual Responsibility Coupled with Communal Sharing. Expertise is distributed deliberately across the members of the learning community and shared in collaborative learning activities such as the jigsaw method (see *Box 1*). The group uncovers together which aspects of knowledge need further investigation and individual students take responsibility for finding out more and teaching this knowledge to others. When children encounter a topic that particularly fascinates them, they can specialize ("major") in this topic.

(2) Multiple zones of proximal development. There is emphasis on desired *diversity* in the classroom, because the essence of team work is to pool varieties of expertise. According to Brown and Campione, there is little (scientific) support for the idea that a prototypical form of development exists that describes when exactly "normal" students are ready to learn certain skills. Therefore, classrooms should be settings for multiple zones of proximal development through which the students move via different routes and at different rates. At any time, learners are ready to learn in some arenas more than in others and classrooms must respect this diversity of talent (for example, by providing multiple ways of learning such as through art, technological skills, reading, writing, and teaching). This leads to a diversity of expertise and interests which is beneficial because it increases the richness of knowledge available.

(3) Ritual, Familiar Participant Structures. There are a few participation frameworks which are practiced repeatedly. The repetitive nature of these activities enables children to make the transition from one activity to another quickly and effortlessly and helps them understand what their role is in each activity. Thus, although there is much room for individual discovery, activities are highly structured so that students and teachers can switch between activities as effortlessly as possible. Examples of classroom routines are reciprocal teaching activities and *crosstalk*, where students report on their progress and other students ask them questions to provide comprehension checks. There are also *benchmark* lessons, where the teacher or an external expert introduces new information, models thinking skills, or encourages the class to pool their expertise in a novel conceptualization of the topic (Brown, 1994).

(4) A Community of Discourse. A community of discourse must be established early, in which constructive discussion, questioning and criticism become the norm. Speech activities involve increasingly scientific modes of thinking, so that students can learn and practice conjecture, speculation, evidence, and proof. The theoretical reason for this emphasis on active exchange of dialogue is that higher thought is seen as internalized dialogue. Therefore, all members of the class are encouraged to adopt a discourse structure, goals, and belief systems of the community.

(5) Seeding, Migration, and Appropriation of Ideas. Learners of all ages, both teachers and students, create zones of proximal development by *seeding* the environment with ideas and concepts. Ideas can then take root in the community, *migrate* to other members, and persist over time. Other members might *appropriate* the ideas and concepts, reshape and deploy them, interpret and transform them, according to their needs and to the current state of the zones of proximal development in which they are engaged. In more applied terms, students as well as teachers can discover during their work or discussions topics of interest or questions that puzzle them. If these ideas catch the interest of other group members, they will modify or interpret them based on their own interests. When the ideas persist over time, they stimulate further research and exploration. Teachers frame the ideas in such a way that under the general umbrella of themes chosen based on student curiosity and interest, the students are introduced to critical underlying notions and deep thinking.

In practice, FCL realizes these principles of learning by integrating the roles of students-as-learners and students-as-teachers with peer-teaching, cross-age tutoring, and techniques like so-called jigsaw puzzles (see Box 1). The aim of these activities is that students act as self-reflective, critical researchers and practice plausible reasoning, explanations, analogy and comprehension-monitoring during reciprocal teaching. The aim is also that students become co-investigators of their own learning, who feel in charge of their learning. The research that the students engage in is intended to create a deep disciplinary understanding (Brown, 1992).

Box 1. Jigsaw in the Community of Learners

One of the FCL methods intended to make students designers of their own learning is a modified version of the jigsaw puzzle (Aronson, 1978 in Brown & Campione, 1994). The authors describe it thus: “Students are assigned curriculum themes (*e.g.*, changing [animal] populations), each divided into approximately five subtopics (e.g., extinct, endangered, artificial, assisted, and urbanized populations). Students form separate research groups, each assigned responsibility for one of the subtopics. These research groups prepare teaching materials […]. Then, the students regroup into reciprocal teaching seminars in which each student is expert in one subtopic, holding one-fifth of the information. Each fifth needs to be combined with the remaining fifths to make a whole unit. All children in a learning group are expert on one part of the material, teach it to others, and prepare questions for the test that all will take on the complete unit. It is important to note that all children are finally responsible for mastery of the entire theme, not just their fifth of the material.”(Brown & Campione, 1994, pp.233-234)

FCL gives students much room for discovery and individual majoring, but at the same time the teacher intentionally directs activities towards relevant content and engineers the curriculum. The teacher hereby ensures that important content is discovered, understood, and transmitted and sets bounds on what is covered. The curriculum is spiral: it features few themes which are revisited several times over the course of schooling and which are each time studied at increasingly deep and complex levels of understanding and reasoning. Each revisit is based on past experience and on the changing knowledge base of the students. Students feel ownership of what they study because they have the freedom to nominate (sub-)units for study. In the beginning of new units, the class discusses what they already know and what they want to find out. Students then browse through selected books to generate questions, which are grouped in sub-units. Activities thus develop as a consequence of the students’ own questions and interests. This is called *appropriation of ideas:* the teacher appropriates students’ spontaneous ideas and encourages them to consider underlying deeper general principles. Like this, the students’ natural curiosity fuels sustained inquiry (Brown & Campione, 1994).

In sum, FCL is a constructivist approach in which teachers help the students discover important curricular concepts framed by the students’ own ideas and questions. Learning routines centre around learning by discovery and research, and prominently feature collaborative learning such as by reciprocal student-student teaching.

Learning by Design and Case-based Reasoning

Learning-by-design (Holbrook & Kolodner, 2000; Kolodner, Crismond, Gray, Holbrook, & Puntembakar, 1998) is an inquiry-based science learning programme with a focus on learning for flexible transfer to new situations. It is based on Case-based Reasoning Theory (Kolodner, 1992): case-based reasoning (CBR) theory was originally developed as a method to implement computer programs that can solve problems based on past experiences (Kolodner, 1992). Its computational models of encoding, retrieval, and adaptation processes in analogical reasoning also provide insight into human cognition and in particular in the function of prior experiences when solving new problems (Kolodner, Hmelo, & Narayanan, 1996), which has led to the formulation of guidelines for education. These guidelines concern, for example, the type of problems that students should solve, ways to manage complex problems, and the kinds of reflection that should be encouraged during learning (*e.g.*, Kolodner, 1997).

The basic assumption of CBR is that reasoners naturally use their own experiences when they deal with unknown or uncertain information during problem solving. In such situations, reasoners try to recall similar previous experiences to find a way of interpreting the situation at hand. Previous experiences can help predict the effects of possible solutions and warn of potential problems (Kolodner, 1992).

According to CBR, previous experiences are saved in the form of so-called *cases* - rich representations of personally experienced situations that include information on the previous situation, the problem or goal at that moment, the way the situation was dealt with, and the results of that behaviour or solution (Kolodner, 1992, 1997). Cases are most useful to solve new problems when they are detailed and contain a thorough analysis of goal achievement. In other words, cases are most informative if they describe clearly under which circumstances the reasoner performed which action, and whether and how this action led to the desired outcome.

CBR assumes that problem solving requires a matching of a new situation or problem and relevant previous experiences, which are encoded in cases. During this matching process, aspects of the description of the situation are used to probe into memory and look for cases that match the probe. The outcome of this search for matches depends on (a) the richness of the cases in memory (*i.e.,* on how well and how completely the reasoner interpreted, articulated and recorded experiences in memory), (b) the richness of the probe (*i.e.*, how well and how completely the reasoner interprets the new situation to identify what is important about it), and (c) on how good the reasoner is at matching the new problem with old experiences (Kolodner, 1997).

Each of these aspects of case based reasoning has clear implications for education (Kolodner, 1997). First, learners need rich cases to draw from because this increases the chance that they can find old experiences that match a new situation. The straightforward implication for education is that students should be stimulated to think deeply about various aspects of the concepts and skills they learn. Concepts should be dealt with from several points of view, and encountered in different situations so that knowledge is complex and flexible. This must entail clear definitions of goals of activities and the evaluation of outcomes.

Second, students must learn how to elaborate on a task at hand to reinterpret and re-represent it in different terms and from different points of view. Thinking about a situation in such a way enriches the description of the situation and thereby increases the chance that cases from memory are found which match some of the characteristics of the situation. A further advantage is that elaborating on the situation also leads to a deeper processing of it, which turns the new situation itself into a rich experience which the learners can remember and later build on.

Third, students must learn how to identify matches between a task at hand and prior experiences. This involves the retrieval of an analogous case from memory, a process that is relatively easy when the new situation is similar to previous experiences but can be more difficult if the match is weaker. Students must therefore practice to identify significant features of a problem, learn how to recognize if an old case or experience is relevant, and learn how important concepts are reused and abstracted in different situations.

More specific educational principles that can be derived from CBR are (based on Kolodner *et al*., 2003):

- *Failure and useful feedback on failures are very important* for learning because they direct the learners' attention to aspects that are critical for successful problem solving. Students need many opportunities to try out their ideas and thereby get direct feedback from experience. The analysis and explanation of failure based on feedback are crucial to refine their knowledge in light of new experiences, and enrich the cases that the students store in memory.

- *Looking forward and thinking about the applicability of knowledge* have a central function. Students should be encouraged to identify what lessons an experience teaches, and to clearly articulate what they have learned and in which context this might be useful again. This will help them remember experiences in such a way that they can later draw from them when solving new problems. A frequently-used method to engage students in this kind of reflection is letting them document their own approach and what they learned from it for other students.

- It can be helpful if learners draw from *documents of others' experiences*, especially when they lack the prior knowledge necessary to work on a complex task. In practice, this is often realized with a case library that contains case descriptions written to help the students identify issues that need to be addressed.

Although CBR suggests which kinds of experiences and reasoning students should have to learn deeply, it does not make concrete prescriptions for classroom activities. Such specific suggestions are part of instructional programmes that were developed based on CBR, such as *Learning by Design* (Kolodner *et al.,* 2003).

Learning-by-design (Holbrook & Kolodner, 2000; Kolodner *et al*., 1998) is an inquiry-based science learning programme with a focus on learning for flexible transfer to new situations. It is based on Case Based Reasoning Theory (Kolodner, 1992) and instructional techniques from Problem-based Learning (Barrows, 1985). The basic idea is that students work on a design challenge (*e.g.*, a self-powered vehicle, an artificial lung, or a locker-organizer) that requires some critical knowledge or skills to be learnt (*e.g.*, Newton's laws of motion, the anatomy of the respiratory system). The design project constitutes an authentic, meaningful context where students learn to make connections with prior knowledge, ask questions, identify relevant knowledge, and discover and practice new scientific concepts. Principles from case based reasoning theory are used to identify the kinds of reflection that most likely enable the students to remember concepts and skills and enable the students to transfer concepts and skills to new problems (Kolodner, 1997).

Learning-by-design is a programme for middle school science classes. Examples of its design-and-build challenges are physical science units asking students to design and build a parachute (to learn about combining forces), or to design and build a miniature car that can go over several hills (to learn about forces and motion) (Kolodner *et al*., 2003). Such projects fit very well with the requirements from CBR - the design process involves investigation, planning, and design, providing rich learning experiences with construction failures as opportunities to revise and correct ideas. The students' desire to create a working artefact is used to motivate them to discuss their decisions, to hear about and reflect on the design rationales of others, to identify what else they need to learn, and to understand the science concepts that allow them to come up with better solutions (Kolodner *et al*., 2003; Kolodner, Cox, & Gonzalez-Calero, 2005). Included in Learning-by-design is a set of ritualized and sequenced activities that help teachers and students develop a culture of collaborative, inquiry-oriented, design-based learning and to avoid common implementation problems (Holbrook & Kolodner, 2000).

In the typical sequence of activities, students begin by encountering a design challenge in a launcher unit in which they can "mess around" with construction materials or objects. Next, the teacher helps the students in whole-class discussions to articulate what they learned while messing about, and to generate, compare and contrast ideas for how to achieve the challenge. The group then identifies which issues the students need to learn more about. Small groups of students each investigate one issue and report their findings to their classmates. This is followed by a new round of trying out what was learned on the design project. Regular presentations and discussions follow each construction cycle and focus on *what has been tried, what has been learned, and how to apply what has been learned*. These presentations force the students to put their thoughts in order so that they can give clear explanations, and motivate the students to practice active listening to get inspiration for their own project from the other students' approaches. Much time is devoted to analyzing and explaining why certain approaches did not work as expected, and to identifying what else needs to be learned (Kolodner *et al*., 2003).

Box 2. Dealing with common implementation problems

Learning by Design materials address common practical problems with the implementation of the programme in new classes. For example, many teachers initially find it difficult to reserve enough time for discussions and evaluations, and instead devote too much time to construction activities. As a consequence, there is a danger that the projects turn into arts and craft activities with little connection to the underlying scientific concepts. Several different solutions have been developed for such implementation problems (Holbrook & Kolodner, 2000):

First, there are worked-out teaching units, beginning with a launcher unit that introduce students and teachers to project-based work forms by means of a series of short challenges that can be completed in a few class periods. Other materials provide ideas for more advanced design projects with a choice of topics that are suitable for inquiry-based learning because they benefit from understanding of key science concepts.

Second, there is emphasis in all units on establishing routines for regular iteration moments and group discussions in which the rationale of design choices is articulated, evaluated and explicitly linked to scientific concepts. To support this, teacher materials specify learning objectives of each activity and provide advice about dealing with possible difficulties.

Third, instead of constructing a complete artifact, the design task can be to improve an existing one. This limits the time spent constructing, and directs the students attention to understanding why certain characteristics of the design-object are crucial for its function.

Fourth, for optimal documentation and assessment of individual student's performance during the design group work, a variety of design diaries, portfolio's and records have been developed in which the students can prepare the group work, document and reflect on what they did and learned, and write about their group experience.

In sum, the case-based reasoning model describes how students use prior experiences during learning and problem solving, and highlights how learning activities should be organized so that students can optimally build on them in the future. Principles of case-based reasoning are put into practice in Learning-by-design projects.

Central Conceptual Structures

The central conceptual structures (CCS) theory by Case describes developmental changes in children's thinking in different cognitive domains, such as children's understanding of numbers, space, and narratives (Case *et al*., 1996). It is a Neo-Piagetian theory, *i.e.*, a theory that incorporates elements of Jean Piaget's now classic account of children's cognitive development (Piaget, 1960, 1970). Like Piaget, Case conceptualized development as a progression through separate stages and interpreted children's thinking as an expression of their developing mental structures. According to CCS theory, the transition from one developmental stage to the next is limited by biological maturation of the brain, more specifically, by the maturation of brain structures for working memory which determines mental processing speed. However, cognitive change is at the same time to an important degree influenced and stimulated by experiences.

What kinds of experience drive cognitive development? Piaget (and likewise Case) assumed that humans are motivated to make sense of the world and to change their way of thinking if they cannot accommodate new situations (Griffin, 2004a). This is called *disequilibrium:* a state in which the current form of thought cannot explain what the learner experiences. Disequilibrium motivates learners to change their cognitive structures. Examples of such cognitive changes are the integration of separate ideas, or the differentiation of aspects of one idea, and in general the movement toward a more complex stage of development. These Piagetian ideas have influenced education for decades, because they interpreted the role of the learner as that of someone who is actively shaping and constructing his knowledge. This role of the learner has inspired various constructivist teaching methods in which learners construct their knowledge through exploration, active participation, and social interactions. However, there are more implications for educational practice than just giving students an active role. Additional implications are (Griffin, 2004a):

- The students' current level of understanding should be used as a base to build on when introducing new ideas.

- The next level of thinking that follows the students' current understanding should be used to design graded sequences of activities that allow the students to move from their current understanding to the next higher level, constructing increasingly complex understandings.

- It is helpful to introduce cognitive conflict, for example, by revealing shortcomings in student's current ways of thinking because disequilibrium motivates students to construct new understandings.

Although these premises have been accepted by most educators today, they are formulated in very abstract terms which are difficult to put into practice (Griffin, 2004a). CCS theory is more accessible in this respect than the original theory by Piaget because it makes predictions about the nature of changing cognitive structures in specific content-domains like numbers, space, and narrations.

Case called these mental structures *Central Conceptual Structures* (*CCS),* and described them as "networks of semantic nodes and relations" that represent children's core knowledge (Case *et al*., 1996). He believed that CCS transform during development from simple to increasingly complex forms, and influence knowledge acquisition by constituting upper limits of the child's processing capacities. More specifically, he saw four major stages of thought, each with several minor sub-stages. Each major stage transition involves the hierarchic integration of two units of thoughts that were before only available independently, while sub-stage transitions involve increasing elaborations of this new unit. For example, at around four years old, children are thought to have two knowledge structures in the number domain - one to make global quantity comparisons (which pile of cookies is larger?) and one to count small sets of objects (How many cookies are there?). However, 4-year-olds cannot use these two principles at the same time. This means that, for example, they do not count the elements of two piles to determine which one is larger. By around age five to six, a major development occurs when the two "precursor" structures become integrated into one single structure, the *central numerical structure* (also called *number line*), in which numbers are conceptualized as an ordered series of words which are linked to quantities. Children begin to understand that some quantities are larger than others and increasingly realize that numbers have a magnitude (*e.g.*, "9 is bigger than 7!"). This enables them to understand that addition and subtraction questions can be answered by counting forward or backward.

What are the educational implications of such descriptions of development? First, sequences of central conceptual knowledge structures define which concepts are central to performance (Griffin, 2004b). These should be taught, especially to children who may not have opportunities to acquire them on their own. Second, sequences identify how children typically construct their knowledge at various age levels, so that teachers can assess students' current level of understanding to identify the knowledge that should be taught next (Linn *et al*., 2002). Measures have already been developed to assess children's level of thinking in some content domains and studies suggest that students can indeed achieve a deeper understanding if the curriculum focuses on step-by-step teaching of a conceptual structure (Moss & Case, 1999).

In sum, CCS suggests that instructional designs should focus on knowledge that is central to competent performance, and make use of models of the manner in which learners typically construct knowledge over the course of development. Instruction should take into account that some children may not have had the necessary everyday experiences to develop crucial central conceptual structures, and should build on the precursor forms of understanding that students demonstrate at earlier ages.

Knowledge Integration and Web-based Inquiry Science Learning

Students grapple with multiple, conflicting, and often confusing ideas while they learn scientific concepts (Linn, Lee, Tinker, Husic, & Chiu, 2006). Teachers can use these ideas as a starting point and design the learning process as one in which students adopt new ideas, sort out wrong ideas, make connections among ideas, develop criteria to evaluate ideas, and form coherent sets of ideas. This process has been called *knowledge integration* (Linn, 2006), and the knowledge integration framework is the base of *Web-based Inquiry Science Environment* (*WISE*) (http://wise.berkeley.edu/).

The knowledge integration perspective is founded on two premises (Linn *et al*., 2002). First, students bring to science class multiple conflicting views of scientific phenomena, often tied to specific contexts, examples, experiences, or situations. Second, learners deliberately develop their repertoire of views concerning scientific phenomena and invest mental effort to sort out, link, connect, critique, and organize their ideas. This effort that students bring to science is the base to improve scientific understanding and make scientific thinking a lifelong process. Instruction should elicit student ideas, add promising normative ideas, and support the process of combining, sorting, creating, and reflecting to improve understanding (Linn *et al*., 2002).

Linn (2006) distinguishes among four major trajectories that students often follow as they construct and modify their set of ideas:

- First, some students tend to *conceptualize* - they start with a broad range of ideas but quickly focus on normative ideas. They often neglect the sources of their original views, and readily embrace abstract principles from instructional materials.
- Second, some students tend to *experiment* - they test and change their (numerous) ideas in different contexts, adding both normative and non-normative ideas to explain observations and make sense of everyday experiences. These students pay attention to intriguing contexts.
- Third, some students *strategize* - they separate the school context from other contexts and seek to succeed with minimal effort, often relying on rote learning and trying to figure out ways to answer questions that are likely to be on the test.
- Fourth, there are students who *contextualize* ideas, that is, they view all ideas in isolated specific contexts instead of seeking connections. This limits their explanations, for example, when they try to argue that two aspects of one principle are separate (*e.g.*, heating and cooling).

In sum, students combine evidence from authoritative statements, experiments they conduct themselves, and persuasive messages in different ways. However, they often lack criteria for distinguishing ideas or evaluating the cohesion of their ideas. Therefore, teaching should enable students to better reconcile their ideas and to develop criteria to sort out ideas so that they can build coherent accounts of scientific phenomena (Linn *et al*., 2006).

Initial knowledge integration studies revealed four ways in which teaching can promote knowledge integration in this way (based on Linn *et al*, 2003):

- Teaching needs to *make science accessible*. This is to facilitate that students can restructure, rethink, compare, critique, and analyze both the new ideas and their established views. Making science accessible means designing science content, but not necessarily simplifying the language or topic. It begins with the choice of a good inquiry question, which should not be too broad but motivate students to study alternatives and trade-offs. Next, students might need a nudge to get started, for example, by following detailed steps for the first inquiry investigation and then less detailed steps in subsequent projects. Whenever possible, projects should connect to personally relevant, complex questions and provide students with experiences that help them reorganize their scientific ideas.

- Teaching should *make thinking visible*. This concerns the thinking of both the teachers and students. The teacher should model scientific thinking to help students understand how problems are solved, for example, by means of simulations and visualizations. The students should be prompted to report on their ideas, critique and analyze their progress, and reflect on the nature of science.

- Teaching should enable students to *learn from others*. When students learn from each other they encounter a broad range of views that help them develop personal criteria for decisions, and make their solutions comprehensible to others.

- Teaching should promote autonomy and *lifelong learning* by engaging students in complex projects in which they practice critiquing, comparing, revising, rethinking, and reviewing their ideas. This helps them to contrast solutions, test potential connections, and solve novel, complex problems.

In order to test these knowledge integration tenets with more topics, teachers, and contexts, WISE was developed in a co-operation between researchers, classroom teachers, and technologists. WISE is an Internet-based platform for middle and high school science activities where students work collaboratively on inquiry projects, making use of information from the web (Slotta, 2004). These projects can take from two days to four weeks, and typically engage students in either *designing* solutions to problems, *debating* contemporary science controversies, or *critiquing* scientific claims found in web sites (Slotta, 2004). WISE projects are created by design teams that include teachers, technologists, pedagogy researchers, curriculum designers, as well as experts from science agencies and museums (Linn *et al*., 2002). For example, during one project designed in partnership with NASA, fourth and fifth graders design a terrarium to compare the growth of NASA fast plants with regular earth plants. Each project is tested extensively to determine how the project design patterns promote knowledge integration, then reviewed by WISE researchers and revised accordingly (Slotta, 2004). The most successful projects become part of an online library.

WISE modules guide students with an inquiry map and use embedded assessments. The inquiry map guides students to articulate their ideas, test predictions, reflect on their progress, monitor and give feedback on each other's work (Linn *et al*., 2006). This enables the students to work independently, without need for constant teacher guidance (Linn *et al*., 2002). Teachers can access student ideas online in real time and use them to tailor instruction to their students' needs (Slotta, 2004). The purpose of the modules is to help students act like scientists, comparing viewpoints, generating criteria for fruitful ideas, formulating arguments, collecting evidence for their own views, and criticizing arguments generated by their peers (Linn *et al*., 2006). They include planning guides for teachers to create a lesson plan around the WISE project (Slotta, 2004).

Design studies using WISE projects have refined understanding of knowledge integration processes and led to the discovery of four interrelated processes that jointly lead to integrated understanding (Linn, 2006):

- *Eliciting current ideas*: instruction that elicits current ideas in different contexts stimulates students to form links and connections among their ideas, rather than isolating ideas in one context.
- *Adding new ideas*: adding new, normative ideas can also lead to knowledge integration. Teachers need to ensure, however, that students do not just add new ideas to existing concepts, but integrate them into coherent mental structures. This is more likely to happen when new ideas make comparisons between situations, draw on accessible contexts like everyday experiences, provide feedback and encourage students to create narrative accounts of their ideas.
- *Evaluating ideas*: criteria to evaluate ideas are important because they enable the students to critically evaluate information from different sources, for example, from the internet and popular publications.
- *Sorting out ideas*: students need to learn to sort out or correct wrong ideas.

Box 3. Design patterns for teacher and learner activities that emphasize knowledge integration (Linn *et al*, 2006)

Orient, diagnose, guide: define the scope of topics, connect them to personally relevant problems, link to prior instruction, identify students' entering ideas, and add other ideas to stimulate knowledge integration.

Predict, observe, explain: recursively elicit student ideas about a topic, demonstrate phenomena and ask students to reconcile contradictions.

Illustrate ideas: model authentic reasoning, make strategies visible, let students try out strategies and reflect on their views.

Experiment: students frame questions, generate methods for investigation, carry out investigations, evaluate, use findings to sort out ideas.

Explore a simulation or create an artefact: framing challenge or contest, test with a simulation or creation of draft artefact, evaluate results, refine solution, connect results to views on topic.

Construct an argument: select question, generate ideas, identify evidence, articulate viewpoint, revise viewpoint based on feedback.

Critique: evaluate ideas about scientific phenomena, formulate and apply criteria

Collaborate: generate ideas, negotiate meaning, respond to group ideas, support views, reach consensus.

Reflect: analyze the connections made between their ideas, monitor own understanding.

In sum, WISE is an internet-based adaptive learning environment in which principles of knowledge integration are put into practice during online collaborative science inquiries. Knowledge integration refers to processes by which students integrate and organize scientific ideas.

Cognitive Tutors and ACT-R theory

One-to-one tutoring is often more effective than whole-group classroom instructions (Bloom, 1984 in Koedinger & Corbett, 2006), but for economic reasons, it is only rarely possible to provide each child with individual instruction. Increasingly, however, computers create opportunities for individual *electronic* tutoring: modern computer programmes are flexible and can adapt to and predict the needs of the user. This flexibility is used in sophisticated software that supports learners by providing individual feedback and on-the-task hints or corrections, and adjusts the difficulty of activities to the skill level of the user. Such intelligent computer tutor systems have been applied to learning, especially in fields like science, technology and mathematics (See VanLehn, 2011 for a recent meta-analysis).

One example of a research-based approach to the use of electronic tutors is *Cognitive Tutors*, a term that describes a range of programmes that had been used by approximately half a million US students already by the mid-2000s (Koedinger & Corbett, 2006) and that focus at topics like algebra, geometry, or computer programming. The aim of these programmes is to design instruction with reference to a cognitive model of the competence that the students learn. These models are based on *ACT-R theory* (Adaptive Control of Thought-Rational), a theory of learning and performance that describes the structure of the brain to explain human cognition (Anderson, Corbett, *et al*., 1995).

ACT-R models assume that competence decomposes into a set of rules, and that learning means gradually acquiring these so-called “production rules” (Anderson & Gluck, 2001). Production rules represent mental connections between internal goals or external tasks and responses; they are an important element of ACT-R models and characterize how students think or reason. The complexity of a skill is regarded as influenced by the set of production rules that must be learned to master the skill (Anderson, Corbett, *et al*., 1995). In addition, most domains also require the acquisition of some declarative information, but this is regarded as relatively problem-free. In contrast, the acquisition of the procedural knowledge that enables the learners to use declarative knowledge in effective actions is considered more difficult, and it requires active engagement of the student in problem-solving practice. The purpose of cognitive tutors is then foremost to provide the learners with such practice. The effectiveness of this practice depends on the way in which students engage in activities and the way in which they experience them. As much as possible, teaching is situated in authentic tasks and the goal structure of problems is made explicit to help students understand how problems decompose into successive sub-goals (Koedinger & Corbett, 2006).

Software based on ACT-R uses detailed models of the gradual acquisition and change of production rules over time. These models are specifically designed for each tutored competence domain and describe learning paths as consisting of successive sub-goals that are solved by applying relevant production rules. For example, when the task in geometry class is to prove that two triangles are congruent, the first sub-goal in the solution path is to prove that corresponding parts of the triangles are congruent (Anderson & Gluck, 2001). ACT-R models take into account that there are often different ways in which students can acquire the same concept or knowledge and also include information on different erroneous routes that students frequently take at certain points in learning. For example, the software can detect mistakes that are likely due to an overly general application of production rules in situations different from those in which they were acquired (Koedinger & Corbett, 2006) and then give feedback tailored to this error so that students can correct their performance and get back to one of the more successful learning paths. If students ask for help, hints are displayed that guide the student toward the next sub-goal.

Cognitive Tutor software continuously monitors student behaviour and estimates the probability that the behaviour is driven by certain target production rules. In this process, the software tries to diagnose the student's intentions by matching the observed student behaviour to paths of cognitive actions from its library. This process is called *model-tracing,* because the student's behaviour is matched to cognitive models (Anderson, Corbett, *et al*., 1995). Given a match, the tutoring system can provide real-time instruction individualized to where the student is in the problem (Anderson, Betts, Ferris, & Fincham, 2010). If the student gives correct answers, the tutor does not comment and allows the student to progress. If the student hesitates, a hint can be given. If the student makes a mistake, the programme provides feedback to bring the student back to the correct solution path. In particular, if the mistake matches a frequent incorrect production rule, a feedback message is displayed to correct that specific error. Furthermore, estimates about the student's knowledge of different production rules are also used to determine when to proceed to new topics or problems.

Box 4. ACT-R theory about Learning by doing

According to ACT-R, human cognition emerges through an interaction of procedural memory and declarative memory (Anderson, John, *et al*., 1995). *Declarative* knowledge corresponds to explicit verbal information or images that we are aware of and can describe to others (*e.g.*, "Paris is the capital of France"). In contrast, *procedural* knowledge describes implicit knowledge about how to do something, which is knowledge that we display in our behavior but are not conscious of (*e.g.*, being able to apply a certain mathematical rule). Importantly, ACT-R predicts that performance knowledge can only be acquired by doing (Koedinger & Corbett, 2006). It cannot be learned passively by listening or observing, but must be induced from constructive problem-solving experiences. Only then can internal cues like personal goals or external cues, like tasks presented by the teacher, become associated with the correct responses in production rules. ACT-R furthermore assumes that declarative and procedural knowledge acquire strength with practice. Thus, even after successful encoding, further practice is important and useful (Anderson, Corbett, Koedinger, & Pelletier, 1995).

In sum, cognitive tutors are intelligent software programmes that provide students with scaffolding, feedback, and assistance, adapted to the individual students' needs. The programmes are based on models of typical learning trajectories and typical misconceptions, which describe learning paths of successive sub-goals and production-rules. By comparing student performance to frequent learning paths, responses can be interpreted and corrected with appropriate feedback. (More information on ACT-R and cognitive tutors is available online at http://act-r.psy.cmu.edu/)

Direct Instruction

The term *Direct Instruction* refers to a teaching programme intended to improve and accelerate learning by means of clear and concise direct communication by the teacher and high rates of student success during extensive guided, sequenced practice. (Note that the capitalised term "Direct Instruction" refers to a specific educational programme, which is different from the more general use of the term to refer to all kinds of explicit teaching using lectures or demonstrations and often contrasted with more exploratory or inquiry-based learning.) Direct Instruction has been developed over the course of the last 40 years, (early publications include Engelmann & Bruner, 1969). The method has repeatedly been shown to improve different learning outcomes including reading and mathematics (Adams & Engelmann, 1996c; Coughlin, 2011), but it is controversial and often met with scepticism due to its prescriptive nature and the strong role of the teacher (for a discussion of common arguments, see Adams & Engelmann, 1996b; Kim & Axelrod, 2005).

The basic assumptions of Direct Instruction are (Adams & Engelmann, 1996a, p.12): First, all students can process information that is given to them and abstract "features" from examples. Second, students generalize on the basis of similarities of features of different examples in a logical way. Third, what students learn is consistent with the teaching they receive. Fourth, students' memory and featureabstraction capacity improves with practice. Following these premises, it was derived that for students to learn a concept, information must be presented in a clear and consistent way. At the same time, if learning fails, this is most likely due to insufficient clarity of instruction and practice. Therefore, Direct Instruction teaching has the purpose to ensure clear communication and an optimal choice of examples during teaching.

Direct Instruction teaching methods can be characterized by three main components (Watkins & Slocum, 2004):

- The content is organised around widely applicable general concepts and strategies, which are explicitly taught following carefully planned sequences of lessons that are structured based on principles of clear communication.

- Direct Instruction provides guidelines for efficient organization of learning, including grouping based on similar student performance level, frequent assessment, and efficient use of teaching time by means of detailed and explicit scripts for the teachers.

- Direct Instruction provides specific suggestions for student-teacher interactions that actively engage all students and allow the teacher to monitor the students' progress, such as choral responding.

The content of Direct Instruction is organized around general ideas and skills that enable students to later go beyond the items taught and apply their learning in new situations. This includes basic skills as well as higher-order thinking skills such as cognitive strategies to solve problems (Stein, Carnine, & Dixon, 1998). The sequence in which skills are taught is planned in such a way that students always have the necessary prerequisite skills for each step and maintain a high rate of success during practice (Engelmann, 2007; Watkins & Slocum, 2004). This is also called *teaching to mastery.* In general, easier (prerequisite) skills are taught before more difficult ones, and typical examples are practiced before exceptions are introduced. Lessons are organized with *tracks*, which are sequences of activities to teach a specific skill across multiple lessons. Each lesson includes activities from several tracks, and skills develop gradually over the course of multiple lessons. The purpose of this organization of learning is to ensure that information is integrated across lessons, and that students do not forget or confuse old skills when a new unit begins (Engelmann & Bruner, 1969).

Direct Instruction formats specify precisely how teachers should present examples, and which explanations, questions, and corrections they should use. The aim of these formats is to help teachers be clear and concise and help the students focus on the important aspects of materials. For example, there are guidelines for the choice of examples (how to demonstrate differences between examples and non-examples in an unambiguous way), the wording of explanations (teachers should use the same wording on all items because variation might create confusion), and error corrections (teachers should model the correct answer, test if the student can repeat it, provide additional practice, and retest the original item after a delay) (Watkins & Slocum, 2004).

Teaching with Direct instruction is initially highly supportive and structured to ensure a high level of student success during learning (Watkins & Slocum, 2004): Teachers model new skills and provide very explicit instruction, using simplified contexts, and prompts to direct students' attention to important aspects of the problem. Then formats gradually shift to let students practice their skills more independently and in increasingly complex contexts. For example, after first overtly saying steps of problem-solving out loud, students gradually learn to perform them "in their head" (Watkins & Slocum, 2004, p. 83). Over the course of learning, massive practice that is initially used to acquire a new skill is replaced by distributed practice over longer periods of time to ensure retention of skills, and feedback is increasingly delayed to create more natural situations.

During Direct Instruction, students work in small groups of similar competence levels (Engelmann, 2007). Groupings are flexible, and can differ per subject, and groupings can also change over the course of the academic year depending on different progress rates. For example, students who learn faster can transfer to more advanced groups. If necessary, teachers use placement tests to form groups. The content of learning is always slightly beyond the students' current competence level, so that they have the necessary prerequisite skills to master the learning objectives (Watkins & Slocum, 2004). On-going assessment is an important feature of Direct Instruction, and it has both the function to provide feedback on the effectiveness of teaching and to provide a measure of each student's progress. Results from tests are used to form and change student groups, to determine the pace of instruction, and to identify areas which require additional practice.

In order to use instructional time efficiently, teachers need to make transitions between activities smooth, have materials at hand, and develop efficient learning routines for their classrooms. Direct Instruction materials contain detailed scripts with explanations, examples, and wordings for each lesson, to relieve teachers of the responsibility for designing and testing each lesson on their own. The teacher's role when using these scripts is described as that of an "actor" (Watkins & Slocum, p.88), who focuses on delivering instruction, adjusting it to the needs of individual students, and solving unexpected problems, but does not have to design himself a clearly scripted curriculum.

Teacher-student interactions in Direct Instruction are designed to maximize the time that students interact with instructional materials and receive appropriate feedback. The reasoning behind this is that the more active responses each student can give, the more learning can take place, and the less likely students are to be distracted or show behavioural problems. In addition, teachers can better monitor their students' performance during active practice. One frequently-used method towards this aim is choral responding with a signal system. In brief, this involves a signal system in which the teacher poses a question, gives the students thinking time, and then provides a cue so that the students respond in unison "on signal" (Watkins & Slocum, p.92).

In sum, Direct Instruction is based on clearly defined and explicitly scripted teaching procedures that were designed to promote clear and unambiguous communication, and to engage all students in active practice with a high rate of success and a minimum amount of errors. (More information on Direct Instruction is available online at the website of the National Institute for Direct Instruction at http://www.nifdi.org/15/)

Higher-Order-Thinking-Skills (HOTS)

HOTS (Higher-Order-Thinking-Skills) is a compensatory programme for educationally disadvantaged students in grades 4 to 8 that teaches general thinking skills through Socratic dialogues (Pogrow, 1995). It was designed by Stanley Pogrow from the University of San Francisco and has been implemented in different American schools since 1983. During daily pullout lessons, small groups of students and a trained teacher engage in challenging dialogues around complex puzzles presented on the computer. The approach is based on the assumption that thinking requirements of content-learning increase strongly after grade 3, so that students who lack practice of sophisticated thinking and an "understanding of understanding" inevitably fall behind. The purpose of HOTS is to help these students develop complex thinking skills so that they can better follow regular classes (Pogrow, 1995). One of the key premises of HOTS is that most students fall behind not because they are not bright enough but because they lack the socio-cultural experiences that develop meta-cognitive skills, for example, because their parents do not engage them in argumentative discussions that are necessary to develop sophisticated reasoning skills. Therefore, the focus of the compensatory teaching activities is to provide the children with extensive practice in complex thinking, to stimulate them to verbalize reasoning processes and to help them discover how strategic thinking leads to successful problem-solving (Pogrow, 2004).

HOTS is based on the assumption that the greatest problem for disadvantaged students is an inability to construct the types of understanding necessary to deal with difficult curricular concepts. For example, they do not know how to handle more than one concept at a time, how to deal with ambiguity or how to have a conversation about ideas. The aim of the HOTS programme is to develop these kinds of general problem-solving skills that enable students to better understand what they are taught during regular classes (Pogrow, 1996). The concepts that are dealt with in HOTS classes are intellectually challenging, so that the students learn to persist and get to experience the satisfaction of reaching a goal after struggling to reach it. During the lessons, the teacher guides discussions in such a way that the students practice key cognitive thinking skills when they resolve ambiguity, construct meaning, and articulate complex ideas and strategies (Pogrow, 1990).

Specifically, the HOTS programme was designed to improve the following general thinking skills (Pogrow, 1987, 1990):

- *Meta-cognition,* defined as the ability to develop, consciously choose, apply, test and articulate strategies to solve problems.

- *Inference of information from context,* such as figuring out the meaning of information or unknown words from context.

- *De-contextualisation* - the ability to generalize or transfer what was learned in one context to new situations and problems.

- *Synthesis of information,* combining information from different sources and identifying those pieces of information that are necessary to solve a problem

A detailed HOTS curriculum was developed that operationalises these skills during Socratic conversations, with the basic idea to use software that interests the students (*e.g.*, games and adventure stories), and a series of questions that provide practice in the above thinking skills (Pogrow, 1999). For example, in order to stimulate meta-cognition**,** students are probed throughout problem-solving activities to explain which strategy they use, how they choose their strategies, which strategies do not work, how they can tell that a strategy does not work, and to make predictions about strategies that might be helpful (Pogrow, 1999).

Inference from context is also initiated in multiple ways, for example, by letting students read interesting stories which have words in key places that students do not understand. Students make guesses about the meaning of these words, and analyze and evaluate their guesses in conversations with the teacher. These conversations model the kinds of prediction that good readers spontaneously engage in during reading comprehension. In order to advance de-contextualization, series of concepts are discussed across many different contexts and students are asked to describe how the use of concepts is the same and different during various problems. This constant discussion of links between different parts of the curriculum provides efficient practice in generalizing concepts.

Finally, the synthesis of information is practiced when students combine information from a variety of sources, or several different types of information, to answer questions (Pogrow, 1999). The amount of information that students have to acquire, interpret, and react to in order to develop successful strategies is increased over the course of practice, and in some units students are deliberately overloaded with information to demonstrate the need for outlining and organized note taking (Pogrow, 2004).

HOTS is a pullout programme for small groups of ten to twelve students who work with a specially trained teacher. The groups meet for 35 minutes a day, four days a week, over the course of one to two years (Pogrow, 1995). In the first part of each lesson, the teacher engages the group in sophisticated Socratic conversations. The focus of these conversations is to get the students to become increasingly comfortable verbalizing complex ideas and to use language in a social setting in increasingly sophisticated ways (Pogrow, 1999). In the second part, the students try to work out a challenge on the computer (see Box 5). The challenges are visually stimulating and motivating to students, but designed in such a way that key elements of information are missing or beyond the students' immediate knowledge. This creates a springboard for student reflections, predictions and discussions. The tasks are designed to be so difficult that the students initially fail, but will become successful when they continue to mindfully process their ideas (Pogrow, 1996).

Although software is used to motivate students, the key component of the HOTS programme is the conversation between teachers and students. The software enables students to directly test their ideas before verbalizing them (Pogrow, 1996), but most learning during HOTS lessons occurs not from the use of the software but from the comprehension-monitoring, context inference and articulation activities practiced during teacher-student dialogues (Pogrow, 1987). Throughout the HOTS lessons, teachers probe the students to articulate their ideas, discuss their findings and approaches, and explain how and why the computer is reacting to their strategies in a certain way. Students are continuously encouraged to examine their strategies and to make predictions what will happen when they make a specific choice, in order to increase the sophistication of their language both in terms of comprehension and articulation (Pogrow, 1995).

Box 5. Making Problems Intriguing: The Word Problem Processor

The puzzles that students work with during HOTS lessons are chosen to be intriguing and motivating for students. Instead of trying to link problems to (adult) real-life, puzzles are often designed around student fantasy and settings of adventure and exploration (Pogrow, 1994). The Word Problem Processor is one example of such a program, in which students interact with a virtual space creature. This programme is part of Supermath, a content-oriented curriculum that was developed as part of the HOTS project (Pogrow, 1995, p.64). The scenario of the World Problem Processor is that the students communicate with a space creature inside their computer. This creature understands English and speaks math. The students write stories to entertain the creature and the creature provides a mathematical solution if the story is clear and not too simple to allow it to speak math. If the creature cannot understand the story, it tells the students why, so that they can revise their story. By constantly trying to understand the creature's reactions, students begin to use comprehension strategies to solve problems. This is combined with ongoing conversations between teachers and students to help the students think about the general implications of the activity. The teachers consistently probe the students' answers for understanding, for example, by repeatedly asking the students to explain why the creature responded to their stories the way it did. Later, when students solve word problems themselves, they intuitively think of how the creature would have reacted. This helps them develop a mental model of how math and language go together.

There are special HOTS workshops in which teachers learn and practice how to lead HOTS classes and stimulate dialogues that train complex thinking skills. For example, they practice to come up with follow-up questions that keep students in a reflection mode during conversation (Pogrow, 1999). Rather than repeating or amplifying student responses, teachers learn to ask students to speak up. The goal of these methods is for students eventually to give sophisticated, complete responses on their own.

In sum, HOTS is a compensatory program during which students engage in Socratic dialogues about ideas and strategies to solve game-based problems on the computer, which provides students with extensive practice in using and verbalizing key general thinking skills such as meta-cognition and inference making. (More information on the HOTS programme is available online at www.hots.org.)

Knowledge Building

Knowledge Building is a constructivist teaching approach that aims to restructure education around goals and processes of knowledge generation (Scardamalia & Bereiter, 2008). Following the premise that although achievements may differ, the process of knowledge building is similar for children and adults, it engages learners of all ages in the full process of knowledge building (Scardamalia & Bereiter, 2003), which includes collective cognitive responsibility for the advancement of knowledge (Scardamalia, 2002).

Conceptually, the main difference between Knowledge Building and other forms of constructivist teaching in learning communities is its emphasis on the importance of ideas as objects of inquiry and improvement in their own right (Scardamalia & Bereiter, 2003). Knowledge Building looks to make the shift from students being learners and inquirers to students being members of a knowledge-building community (Scardamalia & Bereiter, 2006b). The core motivation of activities is to identify and advance the frontiers of knowledge and to produce ideas that are of value for the learning community. Students posing questions and working collaboratively to solve knowledge problems is the main point of classroom work, with their theorizing, reading, writing, experimenting, and discussing all tied to this purpose (Scardamalia & Bereiter, 2006a). Learning is regarded as something that happens at the same time, as "an internal, unobservable process that results in changes of belief, attitude, or skill", whereas "knowledge building, by contrast, results in the creation or modification of public knowledge—knowledge that lives 'in the world' and is available to be worked on and used by other people" (Scardamalia & Bereiter, 2003, p.1370).

Furthermore, Scardamalia and Bereiter argue that such knowledge building activities encompass the same foundational learning of higher-order cognitive skills and collaborative constructivist inquiries as other approaches, but go beyond these by also introducing learners to processes of knowledge creation: "The key distinction is between learning—the process through which the rapidly growing cultural capital of a society is distributed—and knowledge building—the deliberate effort to increase the cultural capital of society."(idem, p. 1371).

Knowledge Building classes make extensive use of a special software environment designed to organize knowledge, the so-called *Knowledge Forum* (www.knowledgeforum.com). It is a discourse medium in which participants work on a community knowledge base by adding, modifying and moving interconnected ideas, which are described in short text *notes,* and graphical representations of networks of ideas or *views* (Scardamalia, 2002). These views display how ideas subsume, contradict, or constrain each other, and the focus is both on exploring the specific connections between ideas and on gaining a broader perspective that embeds ideas in larger conceptual structures. Such higher-level conceptual structures can depart from learning objectives that the students need to work with (*e.g.*, an overview of curriculum standards to which the students connect relevant notes) or be constructed by the students themselves when they search to give meaning to collections of ideas. The software allows users to create increasingly high-order conceptual frameworks, reformulating problems at more complex levels and creating more inclusive views (Scardamalia & Bereiter, 2006b). Participants are encouraged to annotate, quote, build on or link to other participants' ideas in this process, thereby developing a "rise-above" view (Scardamalia, 2002, p.7). Review and revision are possible at any time, with all participants being engaged in peer review and group editorial processes (Scardamalia & Bereiter, 2006b).

Scardamalia (2002) described unique features of Knowledge Building in twelve principles (pp. 9-13), which are summarized below. It is based on principles to guide pedagogy in a variety of contexts, rather than a set of specific activity structures or procedures (Scardamalia & Bereiter, 2006b).

- *Real Ideas and Authentic Problems.* One of the main goals of Knowledge Building approaches is to develop in students a disposition to work at idea improvement (Scardamalia & Bereiter, 2006a), so that problems are *authentic* and arise from the learners' efforts to understand the world.

- *Improvable ideas.* All ideas are treated as *improvable* and participants work continuously to improve the quality, coherence, and utility of ideas. A prerequisite for this work is a classroom culture of respect and trust, so that participants feel safe to point out wrong ideas, articulate half-baked notions, and give and receive criticism.

- *Idea diversity:* Idea diversity is essential for knowledge advancement. To understand an idea means to understand how it relates to other ideas, including those that stand in contrast to it.

- *Rise above*. Creative knowledge building entails working toward higher-level formulations of problems and achieving new syntheses. Ideas are treated as objects of inquiry in their own right, which interact with one another to produce new and more complex ideas (Scardamalia & Bereiter, 2006b).

- *Epistemic agency*. Participants deal with problems of goals, motivation, evaluation, and long-range planning, set forth their ideas, and negotiate a fit between their own and others' ideas. Participants learn that new advances open up new problems and new possibilities for further advancement (Scardamalia & Bereiter, 2006b), which brings schooling close to creative knowledge work at professional level.

- *Community knowledge, collective responsibility.* The aim is the collaborative creation of public knowledge. Team members produce ideas of value to others and share responsibility for the overall advancement of knowledge in the community. Contributions to shared goals are praised and rewarded as much as individual achievements.

- *Democratizing knowledge*. All participants are legitimate contributors to the shared goals of the community; all take pride in knowledge advances achieved by the group.

- *Symmetric knowledge and advancement.* Expertise is distributed within and between communities, resulting from knowledge exchange and co-construction of knowledge.

- *Pervasive knowledge building.* Knowledge building is not confined to particular occasions or subjects but pervades mental life—in and out of school.

- *Constructive uses of authoritative sources*. Participants are encouraged to use authoritative sources, along with other information sources, as data for their own knowledge-building and idea-improving processes. These sources are treated respectfully but critically and evaluated against their contribution to the knowledge-building discourse.

- *Knowledge building discourse.* The discourse of knowledge is aimed at idea improvement; therefore it is committed to progress, common understanding and an expansion of the knowledge base (Scardamalia & Bereiter, 2006b). It involves extensive sharing of knowledge with the purpose of knowledge refinement and transformation.

- *Embedded and transformative assessment.* Assessment is part of the effort to advance knowledge - it is used to identify problems as the work proceeds and is embedded in the day-to-day workings of the organization. Standards and benchmarks are objects of discourse.

In sum, Knowledge Building restructures education around goals and processes to generate and improve community knowledge through collective effort (Scardamalia & Bereiter, 2006b). One instrument for this purpose is the software environment Knowledge Forum, in which participants can display, organize, modify, arrange and connect ideas in text or graphical form in order to develop increasingly complex conceptual frameworks.

Summary and Conclusions

This paper presents the theoretical base and practical recommendations of eight key research-based approaches to teaching and learning, which highlight important principles and practical recommendations for the successful organization of innovative learning environments. This concluding section contains a summary of these approaches, followed by discussion of them in terms of three dimensions of educational practice: a) amount of direction, b) emphasis on ideas versus activities, and c) individual versus community emphasis (see Scardamalia and Bereiter, 2008).

The Approaches in Summary

- Fostering Communities of Learning (Brown & Campione, 1994) is a constructivist approach in which teachers help students discover important curricular concepts framed by the students' own ideas and questions. Learning routines centre around learning by discovery and prominently feature collaborative learning such as by reciprocal student-student teaching in heterogeneous groups.

- Learning by Design (Holbrook & Kolodner, 2000; Kolodner *et al.,* 1998) is an inquiry-based science learning programme based on case-based reasoning models that describe how learning activities can be organized in such a way that students make experiences from which they can draw during later problem solving.

- The neo-Piagetian Central Conceptual Structures (CCS) theory (Case *et al.*, 1996) describes developmental changes in children's thinking and the kinds of experience that are necessary to progress to more advanced developmental stages in specific cognitive domains, such as sense for numbers and space.

- Web-based Inquiry Science Environment (WISE) is an internet-based adaptive learning environment in which principles of knowledge integration are put into practice during on-line collaborative science inquiries. The knowledge integration perspective describes how children handle multiple conflicting views of scientific phenomena (Linn, 2006).

- Cognitive Tutors (Koedinger & Corbett, 2006) are intelligent adaptive software programmes that provide students with scaffolded teaching, feedback and assistance in response to their performance. Performance is analysed by comparing current student behaviour to ACT-R models (Anderson, Corbett, et al., 1995) of typical learning trajectories, which are formulated in terms of successive sub-goals and production-rules.

- Direct Instruction (Adams & Engelmann, 1996c; Watkins & Slocum, 2004) is intended to improve and accelerate learning by means of clear and concise scripted direct instruction by the teacher and high rates of student success during scaffolded practice aimed at active involvement of all students (*e.g.*, signalled choral responding) and a minimum number of errors.

- Higher Order Thinking Skills (HOTS) (Pogrow, 1996) is a compensatory programme during which students engage in Socratic dialogues about ideas and strategies to solve game-based problems on the computer. It is designed to provide students with extensive practice in using and verbalizing key general thinking skills such as meta-cognition and inference making.

- Knowledge Building (Scardamalia, 2002; Scardamalia & Bereiter, 2006b) is a constructivist teaching approach which places strong emphasis on the creation of community knowledge as the driving force behind activities. It frequently uses a software environment in which the users can continuously improve, organize and integrate elements of the group knowledge.

Extent of Direction

Direct Instruction is the most directive method presented here, and although controversial, this technique highlights several key principles for the organization of learning such as the importance of clear, unambiguous communication, the role of prior (prerequisite) knowledge during the step-wise acquisition of complex skills, and the need to monitor students' progress to refine instruction. These principles apply also to those methods on the other side of the scale which focus on less constrained student inquiries, such as Learning-by-Design or Fostering Communities of Learners. With the latter, teachers help their students engage in sustained inquiry and dialogue to generate understanding through their own efforts. These approaches require the teacher to have a good understanding of learning processes, and to closely observe the children's activities and analyze the kind of thinking that they are engaged in at each moment (Brown & Campione, 1994). They additionally require the teacher flexibly to respond to the children's natural curiosity by using the students' own questions as a starting point to develop key curriculum themes and to redefine the own role away from being a (skilful) transmitter of knowledge toward being a guide or mentor who can help formulate questions and discover resources to answer the questions. Pedagogy based on a knowledge building perspective also involves students learning from discoveries and construction, but here activities are framed by a motivation to expand and improve group knowledge rather than driven by curiosity and the wish to pursue individual inquiries. The teacher's role is to help students develop this knowledge building perspective and to focus activities on the improvement of the group knowledge base.

Ideas vs. activities

With respect to the content of learning, it is possible to distinguish between approaches that have a focus on understanding key concepts or acquiring general thinking strategies, on the one hand, and approaches with a large amount of hands-on activities or fact recall concerning specific information, on the other hand (Bereiter & Scardamalia, 2008). All approaches discussed in this paper emphasize the importance of key concepts or big ideas that are learned in depth and can be transferred to different situations. Often, these skills include meta-cognitive skills and problem-solving abilities such as problem analysis, inference making and hypothesis testing.

This reflects a general paradigm shift in education from a focus on the *amount* of knowledge toward a stronger focus on the desirable *structure* or *quality* of knowledge (Schneider & Stern, 2010). For example, Learning-by-Design programmes illustrate how students practice to plan, test, compare, and refine design ideas so that they learn to think about functional aspects and goals of their activities, and remember them in a way that allows them to flexibly draw from their experiences during later problem solving. Another example is the computerized approach WISE, during which students learn to articulate their ideas, test predictions, reflect on their progress, monitor and give feedback on each other's work. This approach stresses how important it is that teachers model thinking and students articulate their reasoning process.

Making the students aware of reasoning processes and helping them develop sophisticated analytical thinking is also the aim of HOTS, a programme for disadvantaged students to learn to "understand understanding" by means of challenging, extensive, Socratic dialogues with their teacher and peers, using computer puzzles. HOTS highlights the importance of providing students with experience using key thinking skills such as meta-cognition, inference making and transfer of knowledge to new situations. It also highlights that *all* students should be engaged in argumentation about complex problems.

Individual vs. Community

A third dimension of approaches to education is the extent of emphasis on the individual versus community. Of the presented approaches, the Direct Instruction, Cognitive Tutor, and Central Conceptual Structures approaches have a stronger emphasis on individual development whereas the other approaches make more extensive use of group work and discussions as a means to motivate students to organize and articulate their thoughts during socially-oriented learning. The techniques with emphasis on individual learning suggest ways to engage all *individual* students in learning activities as much and as optimally attuned to individual performance levels as possible. For example, Cognitive Tutors respond to the user's progress and errors by providing individualized feedback and adapting tasks to the performance level of the user. During Direct Instruction, choral responding techniques are used to make sure that all students are actively engaged in practice during large parts of the instruction.

These methods highlight the importance of engaging all students in active practice at a level that is appropriate to their current performance level, which is a principle that methods with a stronger emphasis on social learning share but realize in a different way. For example, in the Communities of Learners approach, reciprocal teaching is frequently used to motivate students to organize their thoughts and practice communication skills, and students are also expected to learn to listen to others, compare and connect their ideas to those of others, and to derive learning questions from other students' input. Work takes place in heterogeneous student groups more often during the more community-oriented approaches, based on the assumption that students benefit from interactions in diverse groups of learners, where they learn to teach and communicate about their own and others' ideas during social, cooperative learning.

This paper has reviewed a selection of educational approaches, which were developed and refined over the course of repeated design experiments. All approaches are based on a model of learning mechanisms. Some models describe which concepts and strategies students should learn; others focus more on the way in which students acquire concepts and develop skills in response to teaching, as well as on common difficulties during learning and ways to overcome these difficulties. This kind of information forms the pedagogical content knowledge (Schneider & Stern, 2010) that teachers need to plan activities based on a clear idea of the function of each activity for learning, and to direct attention toward those kinds of exploration and communication that help their students to learn and practice relevant concepts and skills.

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