Chapter 2
Complexity, Inquiry Critical Thinking, and Technology: A Holistic and Developmental Approach

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Abstract Among the skill and competency areas being addressed in national education plans and by prominent educators are collaboration, communication, creativity, and critical thinking. In this chapter, a fifth C is added to that list—namely, contemplation. The argument to be presented in this chapter involves two assumptions: (a) technologies can play an important role in developing these competencies, and (b) to be effective in developing the five C's, a holistic and developmental approach seems appropriate. Given those assumptions, the solution approach here is that a learner should be considered as a whole person and not simply a cognitive processor. Moreover, promoting effective learning involves developing stable and persistent changes in what a person knows and can do. Consequently, developing habits of inquiry and reasoning takes time and is not likely to happen in one unit of instruction, nor in one course. The earlier those habits are developed, the more likely they are to persist and to be applied to multiple domains of inquiry.

Introduction

Imagine the following scenario, which is based on a composite of interviews with electronics maintenance technicians in the Air Force. A recent graduate of an electronics technical training school is working with an experienced technician troubleshooting the electronics on an F-16 fighter jet aircraft based on a troubled report that has been received after a flight training mission. The senior master sergeant (the experienced technician) immediately examines the cable housing for radar system. The assisting inexperience airman asks, "Why did you immediately start examining that cable housing unit? The protocol I was taught in electronics school was to first perform a diagnostic that would rule out about half of the likely causes of the

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T. D. Parsons et al. (eds.), *Mind, Brain and Technology*, Educational Communications and Technology: Issues and Innovations,
https://doi.org/10.1007/978-3-030-02631-8_2

problem that was reported." The senior master sergeant replies, "I know F-16s and I also know this particular plane. Loose cable housing is a recurrent problem on this plane, which is why I started here."

Such exchanges are not uncommon and lead some to the conclusion that schooling is wrongheaded or ill-conceived as it is not often connected with real-world problems. The conclusion reflects an assumption that expertise and knowledge are domain specific, and, as a consequence, that learning and instruction need to be focused on authentic problems and meaningful tasks (Brown, Collins, & Duguid, 1988; Charness & Tuffiash, 2008; Collins, Brown, & Newman, 1989). While there is evidence to support the notion of meaningful tasks and domain-specific expertise, the studies in support of those conclusions are most often conducted with adult learners and do not take into account early learning and knowledge development.

The issue addressed in this chapter involves the impact of early learning and knowledge development on subsequent learning and development. While acknowledging that authentic learning is significant, one is not thereby committed to embracing a domain-specific approach to early learning. Merrill's (2002, 2013) *First Principles of Learning* emphasize the notion of using meaningful problems and four treatment stages, which are popularly presented as follows: (1) tell learners relevant information, (2) ask learners if they understand and ask them to demonstrate some understanding, (3) show learners how to apply new knowledge, and (4) have learners demonstrate the application of new knowledge on a variety of problem-solving tasks. This is a robust framework that has been shown to work using more elaborated frameworks such as cognitive apprenticeship (Collins et al., 1989). It is somewhat robust and can be applied to a wide variety of learners and learning tasks if one adds a fifth stage—namely, "rinse and repeat," using a popular term suggested by a student.

In elaborating what tasks are meaningful prior to college, an impressive coalition involving the National Research Council, the National Science Teachers Association, and the American Association for the Advancement of Science, and Achieve (a nonprofit education organization) developed the Next Generation Science Standards (NGSS; see https://www.nextgenscience.org/) that are meant to integrate engineering and science throughout K-12 curricula. These new standards recognize the complexity of scientific reasoning and the value of Merrill's fourth DO component mentioned above. They also represent a step or two away from a strict domain-specific orientation.

The National Technology Leadership Coalition (NTLC; see http://www.ntlcoalition.org/) and the Smithsonian Institution's educational outreach program have examined and responded to the NGSS standards. NTLC came to the conclusion that many of the NGSS standards are not easily supported in schools without substantial training and professional development of teachers. The Smithsonian was involved in the NTLC studies and responded with a number of education kits aimed at helping developing teaching support and expertise.

The impact of NGSS and associated efforts in developing stable and persistent changes in what a person knows and can do remains to be seen. The remainder of this chapter is aimed at challenging strong domain specificity arguments and in developing a theory- and research-based framework for the development of inquiry and critical thinking skills using technology that is likely to persist and be applicable in multiple domains.

Theory and Empirical Foundations

The point of departure for the underlying theoretical and empirical foundations for the framework to be presented is based on the notion of a holistic view of a learner (Spector, 2016; Spector & Park, 2018). The basic view of a person presented in those and other works is that a person is an integrated set of cognitive, physical, and affective attributes which are interrelated and which interact over time to create an individual's personality, habits, and thoughts. A holistic account of learning involves that embodied notion of being a person as well as a perspective that recognizes changes and development. This is not a new concept of personhood in the education and educational technology literature. One can easily find parts of this view in early Chinese and Greek writings (see Spector & Ren, 2015). Moreover, the notion of a person being more than a cognitive processor is widely accepted by psychologists (e.g., Rogers, 1965) just as many medical professionals see a person as more than a collection of physical attributes (McNamara & Boudreau, 2011).

It is commonly accepted that moods change and can affect learning and performance (Brand, 2012; Brand, Reimer, & Opwis, 2007; Spector & Park, 2018). It is also acknowledged that cognition is a dynamic construct and difficult to measure without considering non-cognitive factors (Ifenthaler, Kinshuk, Isaias, Sampson, & Spector, 2011; Ifenthaler, Masduki, & Seel, 2011). In addition, physical and other learner differences are acknowledged to have an impact on learning (Felder & Brent, 2005). Research on individual differences that impact learning should be considered when designing instruction (Bransford, Brown, & Cocking, 2000; Jonassen & Grabowski, 1993). Moreover, the cognitive science construct of mental models is influenced by a number of factors, including learning challenges such as autism and the influence of parents, teachers, peers, and others (Heijltjes, van Gog, Leppink, & Paas, 2014).

The above referenced research and many other studies suggest that communication skills, collaboration, and the ability to be creative all have an impact on learning. Moreover, those influencing factors involve skills, attitudes and habits that exist or are formed (or not) early in an individual's life. As a consequence, when developing instructional strategies and learning activities aimed at promoting inquiry and critical thinking skills, it seems appropriate to initiate that process early in an individual's life.

The situation is further complicated when the focus is on learning to confront and resolve complex problems. Complex problems arise in many domains of inquiry as well as in everyday life. Much of the effort to develop complex problem-solving skills has focused on college students and adults within a particular domain. However, focusing on adults overlooks habits and attitudes formed early in an individual's life, and, in addition, ignores the reality that many of the complex problems that an individual is likely to confront cross over common domain boundaries, which is already acknowledged in the NGSS standards to some extent.

One remaining foundational factor related to an individual learning to deal with complex problems involves habits that influence behavior and decision-making. Dietrich Dörner (1996), a German psychologist, has investigated human failure in solving complex factors. Dörner argues that what makes a problem are (a) many interrelated factors, (b) non-linear relationships among factors, (c) delayed effects of a decision or action, and (d) uncertainty with regard to aspects of the problem situation. Given those factors, there is a tendency for a person to only focus on a familiar part of a complex problem. In addition, people tend to misunderstand exponential relationships and to expect immediate results of an action or decision. In short, many adults have already developed a habit of simplifying and focusing without due consideration of alternative perspectives or a careful examination of assumptions and biases that influence decision-making.

Developing Inquiry and Critical Thinking Skills

Critical thinking is typically associated with concepts and language, which involve purposeful and reflective judgement and logical reasoning (Butler, Pentoney, & Bong, 2017; Halpern, 2014; Ku, Ho, Hau, & Lai, 2014). However, it is not realistic to only consider cognition within a conceptual and language-based approach or in an analysis of critical thinking skills. A more holistic approach that includes biases, dispositions, moods, preferences, and other factors is likely to be more insightful and provide both teachers and learners with useful feedback to improve critical thinking skills. In other words, it is perhaps best to consider critical thinking as an embodied and situated skill that involves both cognitive and non-cognitive factors (Bransford et al., 2000).

Critical thinking is often discussed and analyzed along with problem-solving and decision-making. This seems natural in that critical thinking skills are often required and found useful in solving challenging problems and in making difficult decisions. However, problem-solving and decision-making skills are more domain specific than are the broader critical thinking skills which can be developed in many domains and are probably best developed in a maturing mind (i.e., early adolescence) that is not so engaged in highly domain-specific learning enterprises. This is probably the most contentious ascertainment in this chapter and the one least well supported with empirical evidence.

Critical thinking is also often discussed and analyzed along with creativity, which is perhaps even broader and more difficult to define and operationalize than critical thinking. This is also somewhat natural because challenging problems and difficult decisions often require an innovative approach that goes beyond one's previous experience, training, and learning. In one sense, nearly everyone is creative in that as a person acquires a native language that person begins to use words and phrases in ways that have not entered that person's prior experience. Moreover, people naturally create internal representations (sometimes called mental models) to make sense of the things they experience. Since everyone is creating mental representations to make sense of and react to their experiences (according to mainstream cognitive psychology), everyone could be considered creative. On the other hand, a different account of creativity involves an ability not merely to create something not previously experienced or in one's cognitive repertoire but the ability to change the problem-solving space in a way that the originator of the problem did not envision. In any case, creativity, like critical thinking, arguably spans multiple domains although it might be especially in only a few of the enterprises in which a person engages. One implication of this notion is that formulaic responses to problems may not encourage the development of critical thinking skills. To support this implication, an emphasis on formative feedback is critical in early learning. This involves both positive and challenging feedback, as well as eliciting how and what a learner was thinking (Dwyer, Hogan, & Stewart, 2014; Ku et al., 2014; Milrad, Spector, & Davidsen, 2003; Tiruneh, de Cock, Spector, Gu, & Elen, 2017).

A Nine-Phase Developmental Framework

The above research literature suggests a developmental framework for the development of inquiry and critical thinking skills aimed at primary and secondary school students. The framework begins with the formation of habits of mind with the initial habit of asking questions, followed by having questions. The developmental process proceeds in stages that emphasize exploring answers and explanations. The teacher or teaching system should first model the process—reminiscent of Merrill's Show the application of knowledge and principles phase of instruction. The teacher or teaching systems should not focus on right or wrong in response to students, but, rather, should focus on understanding why a student responded in a particular way and encouraging the student to explore that response or explanation. The goal is not to get an answer right or wrong. It is to understand why something makes sense and what alternatives might exist. Throughout the process, the five C's are developed: communication, collaboration, critical thinking, creativity, and contemplation. Contemplation is generally referred to as self-regulation and meta-cognition in many of the works already cited (see Spector & Park, 2018). Table 2.1 presents the nine phases associated with this framework.

Similar frameworks can be found in some of the works already cited (e.g., Ku et al., 2014; Merrill, 2002, 2013; Milrad et al., 2003; Paul & Elder, 2010; Tiruneh et al., 2017). The point of having nine phasesand calling this a developmental and holistic approach is to emphasize these key ideas: (a) inquiry and critical thinking skills are not likely to be mastered in one course. Years of practice are involved; (b) both cognitive and non-cognitive factors need to be taken into consideration; and (c) formative feedback and stimulating encouragement should be provided throughout the process.

Roles for Technology

Since technology was addressed in the title of this chapter, it is legitimate to ask how technologies might be used to support such a framework. There are many possible ways to use various technologies to help develop inquiry and critical thinking skills

Table 2.1 Nine phases for developing inquiry and critical thinking skills

Development phase	Skills being developed
1. Inquiry and puzzlement	Observing oddities, answering questions, asking questions
2. Exploration and forming explanations	*Finding relevant factors, creating explanations*
3. Evidence and hypothesis testing	Confirming and disconfirming evidence and predicting outcomes
4. Influence and causality	Differentiating coincidence, correlation and causality
5. Explanation and communication	Explaining reasons for beliefs and the quality of evidence to others
6. Coherence and consistency	Identifying inconsistencies and contradictions
7. Assumptions and biases	Recognizing unstated assumptions and identifying biases
8. Perspectives and alternatives	Considering multiple points of view
9. Reflection and refinement	Monitoring progress, adjusting to new evidence, and contemplating processes

(see, for example, http://www.educationworld.com/a_lesson/worksheets/critical_thinking/3-5/). Two specific technologies are the focus of this section: games and conversational interfaces.

A meta-analysis by Wouters, van Nimwegen, van Oostendorp, and van der Spek (2013) shows that games can have a positive impact on learning. Other studies suggest that games with goals that are well aligned with specific learning goals are more likely to have a positive impact on measured learning (Tobias, Fletcher, & Wind, 2014). The logic behind this impact seems to be that given appropriate background knowledge and information and relevant prior experience exists, that time spent on learning with formative feedback (in this case from a game), learning outcomes are likely to be positive. Games often are able to stimulate interest and engagement, resulting in more time being spent in and outside a classroom setting on a learning task. As a consequence, game-based applications to support each of the nine phases indicated above is likely to be productive, especially for young learners.

As a reminder, this framework does not encourage just getting a correct answer. The fundamental of this approach is to encourage exploration, explanation, reasoning, communication with others, collaborating on innovative solution approaches and reflecting on the quality and efficacy of each step along the way. Given those areas of emphasis in the nine phases, and the engagement factor of game-based applications, the second technology likely to be effective is a conversational interface. Having an application talk to learn in a positive and encouraging manner is required in order to encourage exploration, explanation, and the other areas being emphasized. Natural language processing has advanced and can be used in game-based applications. Children are already interacting with devices such as Alexa, Echo, Google Home, and Siri. These technologies are gaining use among children, modelled by parents who want to encourage their children to ask questions and explore explanations (McTear, Callejas, & Griol, 2016).

Concluding Remarks

An effort to implement and evaluate this framework is underway as a collaboration with three universities and NetDragon. One of the universities involved (East China Normal University) has settled on the notion that a game is needed to assess the progressive development of inquiry and critical thinking skills and has a prototype under development and testing. A second university (Beijing Normal University) has a postdoctoral researcher working with the other university (University of North Texas) on the project.

This effort represents a serious effort to take serious games seriously. In other words, measuring outcomes and efficacy is built around the framework and instruments already validated pertinent to that framework. In addition, the effort addresses both cognitive and non-cognitive aspects of inquiry and critical thinking. Finally, the effort embraces a multiyear developmental approach, unlike most efforts to date, to develop inquiry and critical thinking skills.

Given the need for informed, thoughtful and responsible citizens and the increasing complexity of problems that people encounter, it is imperative to take seriously the development of inquiry and critical thinking skills in young children. In a sense, this effort and the associated framework is a return to the ideas and lessons of John Dewey (1910, 1938). It is not too late to take those ideas and lessons into the twenty-first century.

Acknowledgements Support from a yumber of colleagues at NetDragon, East China Normal University, Beijing Normal University and the University of North Texas have contributed many ideas reflected in this chapter.

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