Chapter 2
Systems Thinking Approach to Robotics Curriculum in Schools

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Abstract This chapter presents a systems thinking approach for the conceptualization, design, and implementation of robotics curriculum to scaffold students' learning of important Science, Technology, Engineering, and Mathematics (STEM) concepts and processes. This approach perceives the curriculum as a system of integrated elements and allows for the investigation of the interdependencies amongst the elements and the dynamics of the curriculum as a whole. Through this approach, we believe that students can be provided with robotics curriculum units that facilitate the learning of STEM "Big Ideas" of and about STEM. A STEM "Big Idea" is central to the understanding and application of STEM across a wide range of fields, one that links numerous STEM discipline understandings. Robotics is a rich context in which students can establish deep knowledge and robust understanding of STEM "Big Ideas". Curriculum units based on this systems thinking approach can do much to ensure that students engaged in robotics activities focus not only on the completion of robotics tasks but also on the social construction of integrated networks of authentic STEM knowledge centred around "Big Ideas" of and about STEM.

Keywords Robotics · STEM · Systems thinking · Curriculum

2.1 Introduction

In the process of designing and programming robots, students can learn many important Science, Technology, Engineering, and Mathematics (STEM) concepts and processes (Cejka et al. 2006). Unfortunately, this potential for advancing the learning of STEM through robotics is far from being realized. The challenge is to maintain student interest whilst not missing STEM "teaching moments" that allow

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students to go beyond trial-and-error strategies, behaviours that lead to weak solutions and limited learning (Barak and Zadok 2009).

To address this issue, we are proposing a systems thinking approach for the design and implementation of curriculum units with robotics. A systems thinking approach to curriculum focuses on the core areas of planning, design, implementation, and assessment and examines how these areas are aligned and connected to support students' success in learning (Jasparro 1998). Through this approach, we believe that students can be provided curriculum units to facilitate the learning of important STEM concepts and processes.

We begin by first discussing conceptions *of* and *about* STEM knowledge. This is because conceptions *of* and *about* STEM knowledge influence decisions teachers make about organizing learning experiences, teaching methodologies, and modes of assessment (Bencze et al. 2006). This viewpoint is borne out by a review of educational robotics literature from the last fifteen years. In most exemplary robotics units, there usually is an overt focus on the creation, testing, and advancement of knowledge *of* and *about* robots and the units are usually underpinned by systems thinking conceptions *of* and *about* STEM knowledge. Exemplary units are defined as units where the focus was on "doing with understanding"; that is, the focus of the units went beyond the mere completion of robotics task(s) and extended to the social construction of knowledge *of* and *about* STEM. This is characterized in most cases by an emphasis on STEM "Big Ideas".

A "Big Idea" is a statement of an idea that is central to the understanding and application of STEM across a wide range of fields, one that links numerous understandings into coherent wholes (Charles 2005). By encompassing and connecting concepts, "Big Ideas" *of* STEM can provide an organizing structure for content knowledge about robotics (Silk 2011) and form a basis for facilitating the meaningful learning of STEM knowledge. A sample of STEM concepts is presented in Table 2.1 that have applications within the contexts of robotics activities. The connection of concepts and ideas can help to establish strong conceptual links within and between the STEM disciplines (c.f., Charles 2005; Harlen 2010).

Focusing on "Big Ideas" can facilitate the meaningful learning of STEM knowledge in robotics contexts by helping students connect concepts and showing students how STEM knowledge can provide them with ways of thinking about and making sense of the world (Harlen 2010; Lesh and Doerr 2003). For example, *Proportional Reasoning is central to how the Motion of the robot can be controlled through Programming*, as the relationships between the construction of the robot, the values used to program the robot, and the movement of the robot are often proportional in nature (Silk 2011). Thus, the exploration of proportional reasoning within the context of robotics can enable students to better understand the application of proportional reasoning in their everyday worlds. Furthermore, the exploration of "Big Ideas" can enable students to progress beyond trial-and-error problem-solving strategies in robotics and many other STEM learning activities.

Table 2.1 A sample of STEM understandings within the context of robotics

	Ideas of STEM	Ideas about STEM
Science	Energy (Rockland et al. 2010), Force (Cejka et al. 2006; Chambers et al. 2007; Rockland et al. 2010) Motion (Chambers et al. 2007; Williams et al. 2007)	Inquiry (Rockland et al. 2010; Sullivan 2008; Williams et al. 2007) Process (Sullivan 2008)
Technology	Design (Sullivan 2008) Programming (Cejka et al. 2006; Silk 2011; Sullivan and Heffernan 2016) Systems (Grubbs 2013; Sullivan 2008)	Computational thinking (Berland and Wilensky 2015; Bers et al. 2014; Sullivan and Heffernan 2016), Systems thinking (Berland and Wilensky 2015)
Engineering	Structures (Cejka et al. 2006) Simple machines (Gears, Levers, Pulleys) (Cejka et al. 2006; Chambers et al. 2008; Williams et al. 2007)	Design process (Bers and Portsmore 2005; Cejka et al. 2006; Grubbs 2013; Rockland et al. 2010)
Mathematics	Proportional reasoning (Silk et al. 2010) Ratio (Silk 2011) Distance, Measurement (Grubbs 2013)	Problem-solving (Chalmers 2013; Norton et al. 2007; Sullivan and Heffernan 2016)

Therefore, we are proposing that curriculum units with robotics should be based on a systems thinking viewpoint about STEM knowledge and focus on the construction of "Big Ideas" *of* and *about* STEM. The implementation of curriculum units with robotics centred on "Big Ideas" can do much to ensure that students engaged in robotics activities not only focus on the satisfactory completion of robots but also on construction of authentic knowledge *of* and *about* STEM. This clearly has implications not only for aims and objectives but also for other key elements in the process of developing curriculum units with robotics such as follows:

- Framing robotics learning activities;
- Integrating robotics learning activities into STEM curriculum units;
- Selection and utilization of thinking tools; and
- Design and implementation of assessment.

Each of these four elements will now be discussed in turn during the following sections of this chapter. We conclude this chapter by integrating these elements into a systems framework to facilitate the design of curriculum units with robotics to scaffold the learning of STEM "Big Ideas".

2.2 Framing Robotics Learning Activities

A review of the literature from the fields of *model-eliciting activities* (MEAs), *learning-from-design*, *educational robotics*, and *knowledge-building* indicates that how STEM learning activities are framed influences whether or not they facilitate the construction of STEM "Big Ideas". Therefore, in this section, a system of six principles for framing robotics learning activities to facilitate the construction of STEM "Big Ideas" is presented (see Fig. 2.1).

1. *Foregrounding Principle*: *A robotics learning activity should focus on targeted STEM concepts that are repeatedly foregrounded during the course of the activity.*

   This principle has its genesis in findings from the Robots Algebra Project (Silk et al. 2010), the Programmable Bricks Project (Rusk et al. 2008), Tufts University's Center for Engineering Education and Outreach research (Rogers 2012; Wendell and Rogers 2013), and research conducted by the Robotics@QUT program (Chalmers 2013). A clear outcome from this research is that the content of robotics activities needs to be targeted and precise. This can be achieved by repeatedly "foregrounding" the targeted "Big Idea(s)" during the course of an activity (Silk et al. 2010) and by highlighting particular ideas and concepts in the natural course of working on a project (Rusk et al. 2008).

2. *Sustained Knowledge-building Principle: A robotics learning activity should be meaningful and relevant to students and motivate students to make sense of the situation based on the extension of their personal knowledge and experiences.*

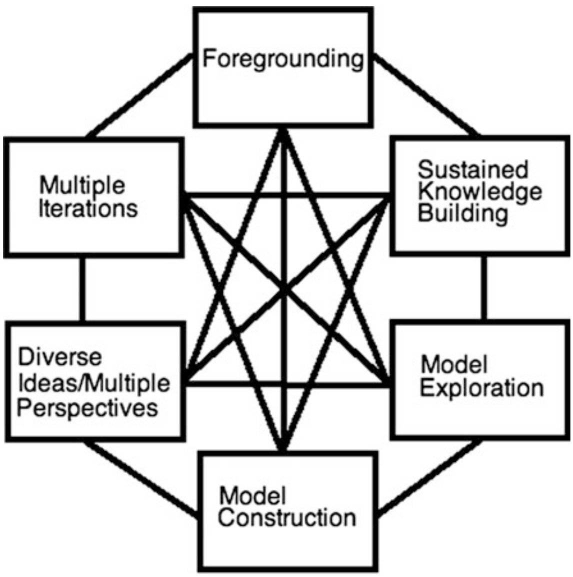

Fig. 2.1 System of principles for framing robotics learning activities

This principle was derived from educational robotics research (e.g. Bers 2008; Bers et al. 2014; Rusk et al. 2008) and MEAs research (e.g. Lesh and Doerr 2003; Hamilton et al. 2008; Yildirim et al. 2010). Different students are attracted to different types of robotics activities (Bers 2008). This clearly implies that teachers need to not only carefully select contexts that can stimulate the interest and involvement of a diverse student population; they also should consider thinking beyond traditional technological approaches when engaged in the process of framing a robotics activity (Rusk et al. 2008). Non-technological approaches such as the social narrative approach (Hamner et al. 2008), the arts and engineering approach (Rusk et al. 2008), the literature and robotics approach (Bers 2008), and the robotics and emotional competency approach (Bers et al. 2014) where robotics becomes a tool rather than the focus of the activity can provide the means for broadening active participation by students with non-technological interests. Motivating active participation in an activity is a necessary but not sufficient condition for sustained knowledge-building. MEAs research has found that to establish and maintain knowledge-building engagement, STEM learning activities also need to motivate students to make sense of the problem context by extending on their personal knowledge and experiences (Hamilton et al. 2008; Yildirim et al. 2010).

3. *Diverse Ideas/Multiple Perspectives Principle: A robotics learning activity should put students in situations where diverse ideas and/or alternative perspectives can emerge and be juxtaposed.*

Research findings from the fields of MEAs (e.g. Lesh et al. 2003) and knowledge-building communities (e.g. Scardamalia 2002) clearly indicate that the development of "Big Ideas" is facilitated if a diversity of ideas and/or multiple perspectives are brought to a problem. MEA research has found that closely juxtaposing multiple perspectives helps students overcome conceptual egocentrism and centring that are especially apparent when unstable conceptual systems are used to make sense of experiences (Lesh et al. 2003). The juxtaposing of different perspectives can help shift focus to the big picture and encourage students to generalize patterns and relationships. Therefore, integrating multiple perspectives encourages students to think more deeply about their experiences.

This principle can be enacted by the following:

- Formation of teams consisting of members with different technical capabilities, different cognitive styles, or different prior experiences (Lesh et al. 2003; Scardamalia 2002);
- Encouraging members of teams to play different roles such as manager, monitor, recorder, data gatherer, or tool operator (Chalmers 2009; Lesh et al. 2003);
- Having students serve as editorial boards that assess strengths and weaknesses of other teams' proposals or by introducing the role of a client (Lesh et al. 2003);

- Utilization of reflection tools to think about group functioning, about roles played by different individuals, and about ideas and strategies that were and were not productive (Chalmers and Nason 2005; Lesh et al. 2003).

4. *Model Construction Principle: A robotics learning activity should create the need for problem resolution* via *the construction/modification of a model that is powerful (in the specific situation), sharable (with others), easily modified, and reusable (in other situations).*

   Research from the field of MEAs (e.g. Lesh and Doerr 2003; Hamilton et al. 2008; Yildirim et al. 2010) and from the Robots Algebra Project (Silk 2011; Silk et al. 2010) has found that requiring students to construct and/or modify a model that is capable of being used by others in similar situations, and robust enough to be used as a tool in other STEM learning can significantly increase the probability that the construction/advancement of "Big Ideas" *of* and *about* STEM will occur. In robotics activities, a model could be a generalizable procedure for designing/constructing a robot, a flowchart, a "how-to" toolkit, a set of rules and/or specifications, a prediction model, a judging scheme, a method, an index, or a metaphor for seeing or interpreting things (Silk et al. 2010).

5. *Model Explanation Principle: A robotics learning activity should require students to explicitly reveal how they generated a model.*

   Findings from MEAs, learning-from-design, and educational robotics research indicate that construction of "Big Ideas" *of* and *about* STEM is facilitated if learning activities are thought-revealing in nature (Hamilton et al. 2008; Sadler et al. 2000; Silk et al. 2010; Yildirim et al. 2010). That is, they require students to reveal not only their models but also the thoughts underlying the development of their models. According to Sadler et al. (2000), students' thought-revealing explanations elicited by the framing of the learning activity should be formative, capturing all attempts and trials. This enables students to examine their progress, assess the evolution of the model, and reflect about the model (Yildirim et al. 2010). With MEAs, model explanation typically involves students writing memo(s) to a client describing their model and documenting how it was developed (Lesh and Doerr 2003). Engineering design research journals and diaries have also been successfully utilized by learning-from-design studies (e.g. Wendell and Kolodner 2014), and in educational robotics research (e.g. Bers et al. 2014; Hamner et al. 2008), to generate thought-revealing explanations by students.

6. *Multiple Iterations Principle: A robotics leaning activity should require students to plan and make multiple iterations to not only to their robotic design but also iterative refinements in understanding of STEM concepts and processes.*

   Taking the time to plan can improve both design product and learning outcomes (Fortus et al. 2004). Unfortunately, students often do not engage in the planning phase of the design process (Rogers and Wallace 2000; Welch 1999). MEA researchers such as Hamilton et al. (2008) have found that this can be addressed by requiring students to present their initial plans (and iterative revisions of these plans) in their reports to clients. This dilemma also can be addressed by constraining the time and resources available for a learning activity; if students are given too much time and too many materials, they often resort to trial-and-error methods rather than advance planning to complete many design problems (Wendell and Kolodner 2014). Ensuring that the artefacts (i.e. robots) to be designed are relatively easy to build and/or modify has been found to facilitate multiple iterations and testings of ideas (Sadler et al. 2000).

Research from the field of learning-from-design indicates that designing a working artefact involves iterative design. Iterative design of an artefact affords opportunities for students to incrementally construct, evaluate, discuss, and revise both the models they are designing and their conceptions (Puntambekar and Kolodner 2005). Iterative design also enables students to learn from their failures as well as their successes (Sadler et al. 2000). However, this iterative process can lead to significant student frustration and discouragement if students do not shift from the typical trial-and-error design process (Bers et al. 2002) and use STEM “Big Ideas” to predict what their robot will do and to choose the best solution (Silk 2011).

2.2.1 Application of the System of Principles

Robotics activities are engaging, however, how the activities are framed influences whether or not they facilitate the construction of STEM “Big Ideas”. As is indicated in Fig. 2.1, the six principles should be conceptualized not as a sequential list but as a system of interrelated principles that are implemented iteratively in cycles with multiple feedback loops. When implemented as a system, the six principles can be utilized to guide not only the design of new robotics activities but also the evaluation and modification of existing robotics activities to ensure that they facilitate the learning of “Big Ideas” *of* and *about* STEM. The principles can help develop curriculum units that focus attention on the “Big Ideas”, promote active inquiry, and support students reflecting on the learning process.

2.3 Integrating Robotics Learning Activities into STEM Curriculum Units

Isolated problem-solving activities such as robotic design tasks are seldom enough by themselves to ensure the learning of STEM “Big Ideas” (Chambers et al. 2008; Silk 2011). Sequences of structurally related STEM learning activities conducted over a number of class periods in conjunction with discussions and explorations focusing on structural similarities amongst the related activities also are needed

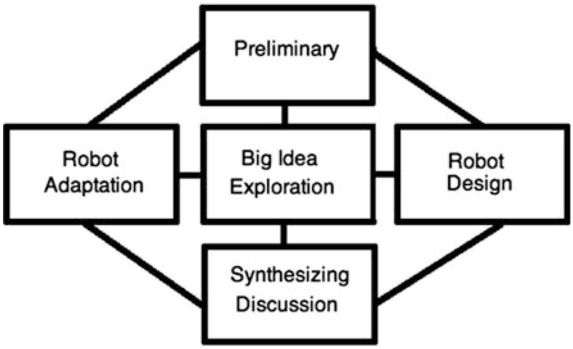

Fig. 2.2 System of modules for developing sequences of structurally related STEM learning activities

(Lesh et al. 2003). Therefore, in this section a system of five modules for developing sequences of structurally related STEM learning activities in curriculum units with robotics is presented (see Fig. 2.2). The system is derived from an analysis and synthesis of research on the design of structurally related activities from the fields of MEAs, learning-from-design, and educational robotics.

2.3.1 Preliminary Activity

The Preliminary Activities familiarize students with the context of a robotics construction task. Familiarizing students with the context of a task can be achieved by providing students with background information via short articles, webpages, and video clips accompanied by questions that:

- Familiarize students with the context of the robotics design problem so that their solutions are based on extensions of students' real life knowledge and experiences; and
- Build up "minimum prerequisites" for students to begin working on the robotics design problem (Lesh and Doerr 2003; Silk 2011).

2.3.2 Robot Design Activity

During the course of each class period when the students are engaged in the process of designing and constructing a robot, teachers can do much to facilitate a culture of metacognition and knowledge-building by asking students questions that require them to:

- Predict outcomes—This can help students to understand what kinds of information they might need to successfully complete the robotic design task (Darling-Hammond et al. 2008; Puntambekar and Kolodner 2005); and
- Monitor what they are doing—For example, “What are you working on now?”, “Why are you working on it?”, and “How does it help you?” (Darling-Hammond et al. 2008; Puntambekar and Kolodner 2005).

At the end of each class period during the course of a Robot Design Activity, the knowledge-building aspects of the activity can be further enhanced by the utilization of Pin-up Sessions, Presentations and Discussions, and Reflection and Debriefing Activities.

In Pin-up Sessions, students periodically present their design ideas and sketches by creating a poster, pinning it to the wall, and then explaining to the class their intentions and how they plan to achieve them (Puntambekar and Kolodner 2005). The primary goals here are to encourage students to think through their ideas deeply and make their reasoning clear. According to Puntambekar and Kolodner, hearing the ideas of others provides grist for students to learn what makes for good justifications. They also argue that Pin-up Sessions give an entire class a chance to consider additional alternatives besides the ones they had considered in their small groups. Additionally, Pin-up Sessions may give groups that are experiencing difficulties a chance to come up to the level of the rest of the class.

Presentations and Discussions are whole-class activities in which students make formal presentations about what they have created and how they created it. The primary goals here are for students to explain their work, see other students’ alternative approaches and outcomes, discuss strengths and weaknesses, and identify directions for improvement for their own work and the work of others. Puntambekar and Kolodner (2005) suggest that Presentations and Discussions should occur between iterations of the design process to provide students with opportunities for talking about STEM ideas and seeing how others are applying them. Because they enable students to engage in discourse about ideas, critique in a constructive way, and revise work after receiving feedback, Presentations and Discussions can do much to facilitate the development of metacognitive thinking skills such as reflecting on and regulating learning (Bers et al. 2002; Darling-Hammond et al. 2008). Lesh et al. (2003) have found that having teams of students produce executive summaries is a most effective means for facilitating knowledge-building Presentations and Discussions and the development of metacognitive thinking. Other means suggested by Lesh et al. (2003) for facilitating knowledge-building Presentations and Discussions and the development of metacognitive thinking include multimedia presentations and having teams of students play the role of clients who give feedback to other teams about the strengths and limitations of their models.

Reflection and Debriefing Activities’ primary goal is to help students assume a reflective and strategic stance towards learning (Darling-Hammond et al. 2008) and adopt an “increasingly productive personae for learning and problem solving (Lesh et al. 2003, p. 50)”. This process can be much facilitated by the utilization of reflection tools that focus not only on solutions, but also on group dynamics and the roles that individual students played during different stages of the solution process (Chalmers 2009).

In order to ensure that student teams do not "give up" when experiencing frustration and/or failure, they should be provided with adequate "self-help" resources such as "*just-in-time*" "*how-to*" *toolkits* (Lesh and Doerr 2003). Examples of such toolkits that could be utilized in Robot Design Activities are online tutorials, simple building and programming instructions, tutorials, video tutorials, and manuals.

2.3.3 "Big Idea" Exploration Activity

The primary goal here is to form a cognitive link between robotics and non-robotics contexts of the "Big Idea(s)" foregrounded in the robotics tasks. Research in the field of robotics in schools (e.g. Chambers et al. 2008) suggests that providing students with physical experiences such as designing robots is not enough by itself for students to develop understandings of STEM "Big Ideas". As Lesh et al. (2003) point out, to help students go beyond thinking *with* a "Big Idea" and also think *about* it, several structurally similar embodiments are needed. Students also need to focus on similarities and differences as the relevant "Big Idea(s)" function in different contexts. Thus, students must go beyond investigating individual ideas to investigate structure-related relationships amongst several alternative embodiments —perhaps by making translations or predictions from one context to another.

2.3.4 Robot Adaptation Activity

The primary goal here are to have students deal with robotics problem(s) similar to but more complex than those addressed in a Robot Design Activity and whilst in the process have them adapt and/or extend the "Big Idea(s)" developed and refined in the Robot Design and/or the "Big Idea" Exploration Activities. A good example of a Robot Adaptation Activity is provided by the Robot Synchronized Dancing Activity created by Silk (2011). In this activity, students were required to create a "how-to" toolkit to coordinate the physical features, program parameters, and robot movements of many different existing robots so that they can "dance in sync" with each other.

2.3.5 Synthesizing Discussion

Synthesizing Discussions are conducted during the concluding phase of a sequence of learning activities (Lesh et al. 2003). These discussions provide closure and have students go beyond thinking with the foregrounded "Big Idea(s)" and advance towards making the "Big Idea(s)" explicit knowledge objects of thought that serve in the further advancement of knowledge. Knowledge-building and MEA research indicate that this process can be facilitated by whole-class teacher-led activities that focus on structural similarities and differences between the different embodiments of the "Big Idea(s)" explored during the course of the sequence of learning activities.

2.3.6 Application of the System of Modules

Because they are conceptualized as a system, the modules can be sequenced in different ways to facilitate the:

- Introduction of "Big Idea(s)" through robotics;
- Application and Extension of "Big Idea(s)" through robotics; and
- Introduction, Application, and Extension of "Big Idea(s)" through robotics.

Thus, the sequence in which the modules are applied to structure a curriculum unit with robotics can be varied to meet the needs/preferences of teachers/researchers. For example, if a teacher/researcher wanted to introduce the STEM ideas of rotational speed and torque through robotics, the unit could begin with a Preliminary Activity where students are presented with a real-world situation establishing the need for the development of a set of specifications (i.e. a model) for the design of a rescue vehicle capable of travelling across flat surfaces quickly, but also able to negotiate steep hills. During the process of developing and refining the model during the Robot Design Activity, the teams of students could investigate what gear trains yield the best compromise between rotational speed and torque and develop key science/engineering ideas such as follows:

- Gearing down will slow down your robot but will supply more power for climbing; and
- Gearing up will speed up your robot but will supply less power for climbing.

In order to extend the understandings of rotational speed and torque developed during the course of the Robot Design Activity, these understandings could be further developed in non-robotics contexts such as bicycle gears during the course of the "Big Idea" Exploration Activity. They also could be extended in the Synthesizing Discussions where the notion that gears work on the principle of mechanical advantage can be explored and generalized across different contexts.

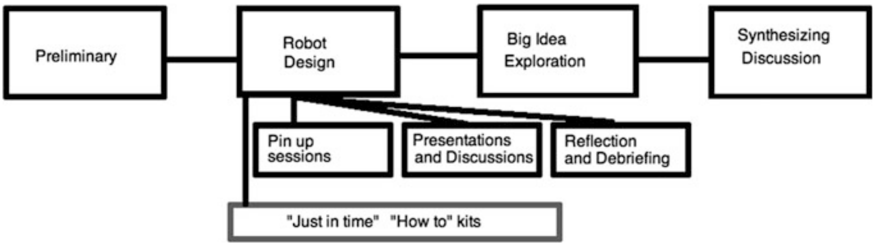

Fig. 2.3 Introduction of "Big Idea(s)" through robotics

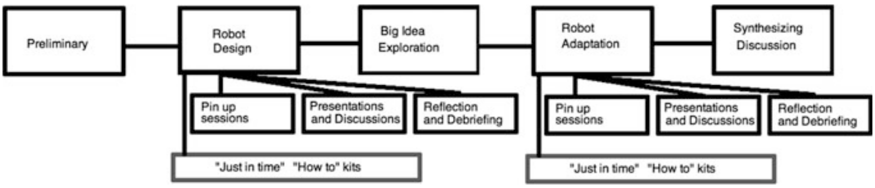

Fig. 2.4 Introduction, Application, and Extension of "Big Idea(s)" through robotics

One application of the system of modules for structuring learning activities is encapsulated in Fig. 2.3. In this structuring of the modules, "Big Idea(s)" are introduced in the context of robotics design tasks. The "Big Idea(s)" foregrounded in the robotic learning activity are further explored and extended during the course of the "Big Idea" Exploration Activity and Synthesizing Discussions.

The application of the system of modules encapsulated in Fig. 2.4 is similar in most respects to that encapsulated in Fig. 2.3. The major difference is the inclusion of the Robot Adaptation Activity where students deal with robotics problem(s) similar to but more complex than those addressed in a Robot Design Activity.

Other different ways for utilizing the system of modules to apply and extend "Big Idea(s)" through robotics are illustrated in Fig. 2.5. In this structuring, the initial preliminary or "Big Idea(s)" activities are explored first and then students are required to extrapolate and apply their understandings of STEM "Big Idea(s)" foregrounded in these activities to scaffold the design, construction, and programming of their robot during Robot Design and/or Robot Adaptation Activities.

As was noted earlier, the sequence in which the modules for developing sequences are utilized to structure a curriculum unit with robotics with a focus on STEM "Big Idea(s)" Exploration can be varied to meet the needs/preferences of teachers (and researchers). However, whilst in the process of framing robotic learning activities and integrating them into a sequence of structurally related STEM learning activities, teachers (and researchers) also need to concurrently consider how thinking tools can be utilized during the course of the curriculum unit with robotics to further scaffold the learning of STEM "Big Ideas".

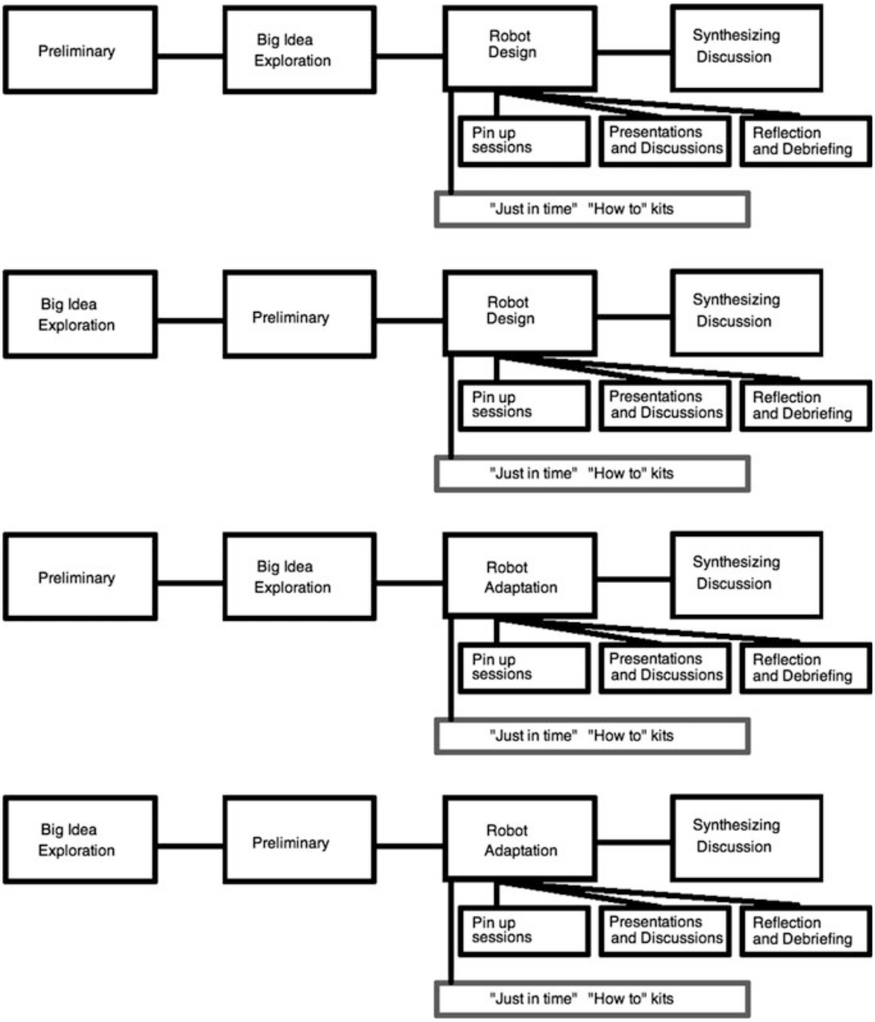

Fig. 2.5 Application and Extension of “Big Idea(s)” through robotics

2.4 Selection and Utilization of Thinking Tools

Thinking tools have important roles in supporting the learning of “Big Ideas” *of* and *about* STEM during the course of design activities (Kokotovich 2008; Puntambekar and Kolodner 2005). Therefore, decisions about what thinking tools can be utilized and how they should be utilized during the course of a curriculum unit with robotics need much thought. To facilitate this process, in this section we present a system for the selection and utilization of thinking tools (see Fig. 2.6).

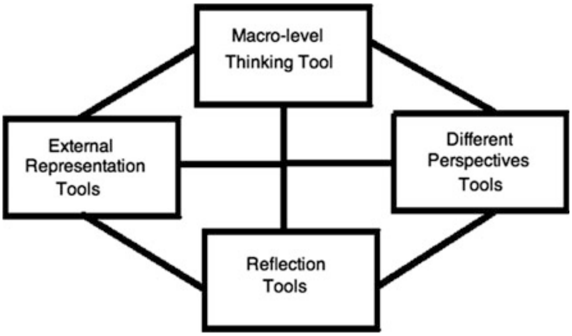

Fig. 2.6 System for selection and utilization of thinking tools

Table 2.2 Macro- and micro-level thinking tools

Micro-Level Tools		Macro-Level Tool: Design Process					
		Define Problem	Explore Ideas	Plan/ Design	Create/ Implemen t	Test/ Improv e	Share Solution
External representati on tools	Concept maps						
	Flow charts						
	Tables and graphs						
	Construction diagrams/ plans						
Different perspectives tools	Improvement triggers						
	Six thinking hats						
	Memos to clients						
Reflection tools	Task-work						
	Team-work						

Research literature from the fields of *learning-from-design* and *educational robotics* indicates that both macro- and micro-level thinking tools are needed to facilitate learning. Thus, our proposed system consists of three types of micro-thinking tools (external representation tools, different perspective tools, and reflection tools) integrated into the operation of a macro-level tool (see Table 2.2).

2.4.1 Macro-level Thinking Tools

A macro-level thinking tool (e.g. the Engineering Design Process) provides students with a global framework to guide them through the major steps of the design process whilst also enabling them to go back when necessary to earlier steps to make modifications or changes to a design (Puntambekar and Kolodner 2005). The ultimate goal of these macro-level tools is to help students to create the best design possible by improving it over and over again. These tools are not linear but cyclical in nature. This means that each of the steps in these tools may be repeated as many times as needed, making improvements along the way. For example, after testing a design and finding a problem, the macro-level tools allow you to go back to an earlier step to make a modification or change to a design.

2.4.2 Micro-level Thinking Tools

Within the design process, micro-level tools usually have three main roles:

- Generating external representations;
- Looking at a design problem from different perspectives; and
- Promoting reflection.

2.4.3 External Representation Tools

External representation tools (such as those listed in Table 2.2) facilitate the construction of external representations that help learners to collect, organize, absorb, and understand information, advance knowledge (Caviglioli et al. 2002), and make sense of messy situations inherent within many design tasks (Fathulla and Basden 2007). During the early steps of the design process, external representations mediated by these tools help learners to structure and map the salient issues, thoughts, and ideas relevant to a design problem (Kokotovich 2008). The construction of the external representations during the early steps of the design process also helps students to think logically about the problem and define it in a more holistic way, rather than just jumping in and relying on trial-and-error strategies (Kokotovich 2008; Norton et al. 2007). This places students in a position to develop more considered responses to the design problem.

The external representations mediated by these tools also enable learners to identify and externalize their models of understanding (Caviglioli et al. 2002) and make their thinking visible during the middle and later phases of the design process (Lane 2013). By making their thinking visible, learners are able to further analyse their understanding of a design problem and add to, adapt, and change particular aspects of their model of understanding (Caviglioli et al. 2002). As Lane (2013) points out, the rigour of creating an external representation such as a diagram, iterating it through several revisions and of clearly specifying the purposes and assumptions behind it is enough to change an individual's thinking about a design problem just as writing text helps organize and present one's thoughts to others.

Thus, these tools have the potential to facilitate learning throughout the whole design process. This places students in a position to develop more considered responses to the design problem. The external representation generated by these tools can play important roles in facilitating planning how-to approach a design problem, monitoring progress towards the solution to the problem, and evaluating progress towards the completion of the task (Norton et al. 2007).

These thinking tools can also facilitate the advancement of learning and understanding at the group level during all steps of the design process (Lane 2013). The creation of external representations during early steps of the design process enables each learner to share his/her thinking or understanding of a design problem with other students and mediate the development of shared knowledge and understanding about the problem. In order to develop a shared understanding and knowledge of a problem, group members must first negotiate a shared external representation or model of the problem (Chalmers 2009; Fiore and Schooler 2004). Shared external representations facilitate the process of articulating students' thinking and allow group members to formulate an accurate shared understanding (Cannon-Bowers and Salas 2001).

During the middle and later steps of the design process, a shared external representation can provide a focus for discussion and contribute to the collective manipulation, reconstruction, and reinterpretation of information and ideas (Lane 2013). The collective manipulation, reconstruction, and reinterpretation of information and ideas mediated by iterative modifications of shared external representations scaffold the advancement of understanding and knowledge by the group (Scardamalia 2002).

2.4.4 Different Perspective Tools

When teams of students engaged in design tasks seem entrenched in a particularly unproductive mindset (e.g. focusing on trial-and-error strategies) and/or are confronted by impasses (e.g. finding that the artefact they are creating does not work as well as expected), they more often than not are not utilizing metacognitive thinking and systematically reasoning about what they could do to move forward (Puntambekar and Kolodner 2005). This can be addressed by the utilization of thinking tools such as Improvement Triggers (Eberle 1997) that enable students to look at the design problem from different perspectives. Improvement Triggers are a list of SCAMPER (Substitute, Combine, Adapt, Modify, Put to another use, Eliminate, Reverse) questions that can help students look at their work from different viewpoints. These questions can focus on robot design/construction issues (e.g. Adapt: What ideas could we use to adapt or readjust to improve our robots? What other ideas could we use for inspiration for our robots?) and/or the relationships between STEM “Big Ideas” and robotics (e.g. Eliminate: How could we streamline or simplify our models? What elements of our models could we remove?). Other tools that can be used for this purpose are: Six Thinking Hats (de Bono 1985) and Memos to Clients (Lesh and Clarke 2000).

2.4.5 Reflection Tools

Reflection tools have important roles in promoting reflection about task-work and team-work prior, during and after the completion of design problem activities (Chalmers 2009; Hamilton et al. 2008). Reflection tools help students recall and then record significant aspects about what they have done and thus enable students to: (a) relate new knowledge to their prior understanding, (b) mindfully abstract knowledge, and (c) understand how their learning and problem-solving strategies might be reapplied (Hmelo-Silver 2004).

Many external representation and different perspective tools can be utilized to promote reflection about task-work. Reflection about task-work also can be facilitated by sets of reflection questions that students are required to answer following a robotic activity. These questions can be the focus of the class discussions that follow the activity (Hamilton et al. 2008). A review of the literature (e.g. Hamilton et al. 2008; Lesh et al. 2003; Silk 2011) indicates that reflection questions should focus not only on robot design and construction but also on relationships between the robotics activity and STEM concepts and processes.

Research literature from the fields of MEAs (e.g. Hamilton et al. 2008), collaborative learning (e.g. Barron 2000), cooperative learning (e.g. Johnson and Johnson 2004), and team-work (Beatty and Barker 2004) indicates that reflection on team-work can also be facilitated by tools that attune students to:

- Individual roles (e.g. How did your individual roles change during the course of the design process and why?);
- Organization of group-work (e.g. How did you organize your group-work? What strategies did your group use to develop new ideas, interpretations or hunches?);
- Monitoring and improvement of team-work (e.g. How were good ideas shared within your group? What are two things your group is doing well and one thing that needs to improve? How did you monitor the effectiveness of your group-work? What could you do to improve the effectiveness of your group?);
- Problems encountered and how they were resolved (e.g. What problems did you encounter in working as a group and how did you resolve them?); and
- Planning for the future (e.g. If you were to embark on a second, similar task as a group, what would be different about the way you go about working, and why?).

2.4.6 Application of the System of Thinking Tools

A review of the literature indicates that for optimal impact on student learning, thinking tools need to operate in a synergic manner to:

- Help students recognize what step of the design process they are in and to record ideas and knowledge relevant to that step;
- Provide prompts and explanations to help students decide how-to move forward during each step of the design process;
- Provide guidance for students both in carrying out design activities and reflecting on them in order to learn from them; and
- Encourage students to think about and articulate what they have done and why without diverting too much of their time from the raison d'etre of a curriculum unit, the construction of robotic artefacts and STEM "Big Idea" knowledge artefacts (Bers et al. 2002; Lesh and Clarke 2000; Puntambekar and Kolodner 2005).

The clear implication of this is that the number of micro-level tools subsumed within the operation of the macro-level tool needs to be limited. However, this is not necessarily a problem; each micro-level tool can be utilized more than once during the design process (see Table 2.2). Indeed if maximum impact is desired, then each selected micro-level tool should be utilized more than once during the course of the curriculum unit (Lesh and Clarke 2000; Puntambekar and Kolodner 2005). Therefore, limiting the number of micro-level tools utilized within a curriculum unit with robotics probably has positive rather than adverse effects on student learning, especially if each of the selected micro-level tools is utilized in multiple steps of the design process.

2.5 Design and Implementation of Assessment

Because assessment sends a clear message to students about what is worth learning, how it should be learned, and how well we expect them to perform it is imperative that assessment be philosophically consistent with the pedagogical framework implicit in the learning activities. This system is consistent with the constructionist framework (Papert 1980) implicit in previous sections of this article. The system is derived from an analysis and synthesis of the literature from the fields *model-eliciting activities*, *learning-from-design*, *educational robotics,* and *assessment theory*. Therefore, in this section we present a system for the design and implementation of assessment in curriculum units with robotics (see Fig. 2.7). Focussing on both summative and formative assessment this system of gives teachers opportunities to assess the learning process as well as the end product.

As is indicated in Table 2.3, our system has four categories of artefacts. The four categories identified address both formative and summative assessment. Category A

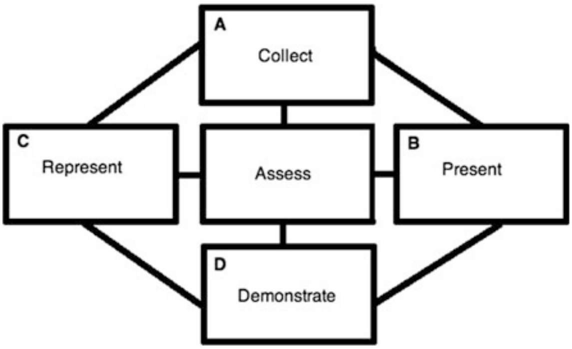

Fig. 2.7 System for the design and implementation of assessment

Table 2.3 Assessment artefacts

Category	Purpose	Assessment Artefacts
A. Collect	Collection of work selected to document progress within a given task	Portfolios[a]
		Engineering design notebooks[a]
		Robot design journals[a]
B. Present	Presentation of prototype(s), description of design solution and process, and description of rationale for arriving at their solution	Presentations[a]
		Demonstrations[a]
		Reports/Memos
		Poster sessions[a]
		Video journals[a]
		Exhibitions[a]
C. Represent	Representation of students' understanding of STEM concepts/processes	Representations produced with Representation Generating Tools[a] (see Table 2.2)
D. Demonstrate	Demonstration of students' understanding of STEM concepts/processes and robotics product (s) and processes	Observations[a]
		Interviews[a]
		Exams
		Reflective essays
		Robot challenge

[a]Change over time in the level of sophistication and complexity assessed

artefacts operate at the macro-level throughout the course of a curriculum unit and consist of a collection of student's work selected to document progress within a given task. Category A collections integrate data derived from Category B and C assessment artefacts. Category B artefacts consist of presentations of prototypes, descriptions of design solution and process, and justification of how students arrived at a solution. Category C artefacts focus on the representation of students' understanding of STEM concepts/processes. Finally, Category D artefacts demonstrate students' understanding of STEM concepts/processes and their robotics product(s) and processes. The data derived from Category D assessment artefacts complement data derived from Category A-C artefacts.

2.5.1 Application of the System for the Design and Implementation of Assessment

The selection and administration of the artefacts are directed by assessment rubrics. These rubrics define the criteria for assessment, the qualities that will be assessed, and levels of performance (c.f., Brookhart 2013). It is important that the selected artefacts and the rubrics utilized for summative assessment focus on assessment *about* learning and during formative assessment focus on assessment *for* learning (Black et al. 2008; Caitlin 2012). Through assessment for learning, teachers can ascertain students' knowledge, perceptions, and misconceptions and use this information to diagnose students' needs, provide them with constructive feedback, and plan interventions to support students to operate at the edge of their competence. Caitlin (2012) identified three essential elements of assessment for learning: Learning Intentions and Success Criteria, Quality Interactions and Feedback, and Peer Assessment. Together, these elements can provide students with prompts they can use to improve their quality of work, helping them feel in control of their learning (Stiggins et al. 2007), shaping, and improving their competence by short-circuiting the randomness and inefficiency of trial-and-error learning (Sadler 1989).

Learning Intentions are not learning aims or objectives but instead a student perspective; it also is about what students will learn, not what they will do (Caitlin, 2012). Caitlin suggests that where possible, the *Success Criteria* in curriculum units with robotics should focus on demonstration and process explanation. Teachers should establish Learning Intentions and Success Criteria by negotiation and students should record these on a pin-up board. Making them visible acts as a reference point throughout the activity helps keep students on task.

Quality Interactions and Feedback generally come in the form of teacher comments and/or guiding questions that encourage students to express and share ideas. Quality Feedback has to "strike a balance between students recognising what is good about their work, as well as what is necessary to improve" (Caitlin 2012, p. 7).

Peer Assessment can also assist students monitoring their learning and they can use the feedback from this monitoring to make adaptations and adjustments to what they understand (Earl 2003). The focus on student reflection is powerful in building metacognition and an ability to plan for future learning goal.

Whilst formative assessment needs to be consistent with the constructionist pedagogical framework underlying the learning activities (Wiggins and McTighe 2005). Summative assessment should also focus on determining to what extent the instructional/learning goals of the unit have been met (Stiggins et al. 2007). Adapting and applying the artefacts utilized in formative assessment for use in the summative assessment at the end of a curriculum unit can facilitate this. This integrates assessment into the teaching/learning process and encourages the active involvement of students in their learning (Earl 2003).

2.6 A Systems Framework to Facilitate the Design of Curriculum Units with Robotics

In this section, the four systems presented in the previous sections are integrated into a systems framework to facilitate the design of curriculum units with robotics that scaffold the learning of important STEM "Big Ideas" (see Fig. 2.8). At the core of this framework are STEM "Big Ideas".

There are many equally appropriate potential pathways in which the framework could be applied to facilitate the process of designing a curriculum unit with robotics. For example, the framework could enable teachers/researchers to begin the process by designing in order: the robotics learning activities, the sequence of structurally related STEM learning activities, the thinking tools, and finally the assessment artefacts and their associated rubrics. On the other hand, teachers/

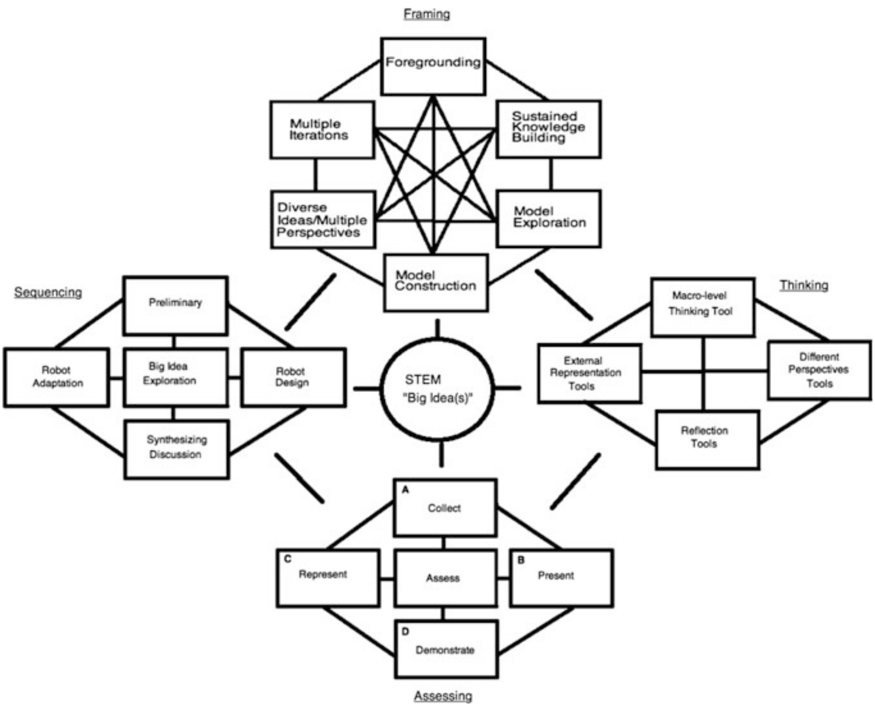

Fig. 2.8 Systems framework to facilitate the design of curriculum units with robotics

researchers also could utilize the framework to engage in "backward design" (Wiggins and McTighe 2005) and first work on the development of the assessment artefacts and their associated rubrics and have the assessment serve as a guide for directing the design of appropriate learning and thinking tools.

However, whatever pathway is utilized, it is important to note that the framework requires that teachers/researchers to conceptualize that:

1. The design of a curriculum unit with robotics is an iterative process (i.e. each element of the framework is revisited on multiple occasions during the design of the curriculum unit); and
2. STEM "Big Idea(s)" are at the core of the framework: therefore, constant recourse to them needs to be made during the design of a curriculum unit with robotics.

2.7 Concluding Remarks

This chapter has presented a systems framework to facilitate the design and implementation of curriculum units with robotics that scaffold not only the successful completion of robotics design tasks but also the construction of "Big Idea (s)" *of* and *about* STEM. We believe that our framework has implications for both practice and research. It provides teachers with both micro- and macro-means for improving the quality of teaching/learning of STEM in units with robotics. For example, at the micro-level the system for framing robotics activities provides teachers with the means to evaluate and improve the quality of robotics learning activities. At the macro-level, the overall framework enables teachers to integrate the planning and implementation of assessment and thinking tools within their units. At the same time, the framework also provides researchers with a number of possibilities for further research. For example, it offers researchers and teachers with a framework to engage in multi-tiered design experiments (Lesh et al. 2008) that could investigate the interactive development of knowledge by students and teachers involved in curriculum units with robotics.

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