Chapter 2
The Teaching and Assessment of Inquiry Competences

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Introduction

As described in Chap. 1, the educational standards in many countries reflect the transition from content-oriented towards competence-oriented learning goals. The sustainable implementation of these new learning goals, however, requires changes both in the teaching and the assessment of these goals. Within the field of science education, a fundamental approach of competence-oriented teaching is based on the concept of scientific inquiry or, as it is more recently called, scientific practices (e.g. Abd-El-Khalick et al. 2004; National Research Council 1996, 2012). From a European perspective, several high-level reports have identified scientific inquiry as one means to improve science teaching thus addressing the increasing discussion in Europe about the need to recruit more young people to careers in science and engineering in order to ensure economic development and welfare (e.g. European Commission 2004; Rocard et al. 2007). Despite its prominent role in science education research within the last 20 years, however, the concept of scientific inquiry is not uniquely defined (e.g. Abd-El-Khalick et al. 2004; Furtak et al. 2012). The

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situation becomes even more complex by looking across domains. In mathematics and technology education, inquiry-based approaches also exist but usually go under different names. In mathematics education, they are often related to problem solving, in technology education to design processes. Innovation can be regarded as a cross-curricular inquiry-based approach to the teaching and learning of twenty-first-century skills since it requires competences from different domains in order to solve problems from different areas of practice. Although no general definition of inquiry exists within and even less across domains, inquiry-based approaches share some common characteristics like the active engagement of students in the thinking and working processes of scientists with the aim of solving complex problems of a personal, societal, environmental or disciplinary nature.

In all domains, moreover, teaching for inquiry confronts teachers with new challenges. It implies a shift in emphasis away from teachers presenting information and covering content-related topics towards teachers as facilitators by creating 'environments in which they and their students work together as active learners' (National Research Council 1996, p. 4). Taking science again as an example, inquiry-based teaching requires teachers to constantly 'guide, focus, challenge, and encourage student learning' (National Research Council 1996, p. 33), e.g. by orchestrating discourse among students but also by modelling 'the skills of scientific inquiry, as well as the curiosity, openness […], and scepticism that characterize science' (ibid, p. 32).

Changing teaching practice, however, requires time and support from the educational system. An important aspect in this context is that changes in teaching need to be accompanied by changes in assessment in order to be sustainable. Assessment is one of the most important driving forces in education and a defining aspect of any educational system. Assessment signals priorities for curricula and instruction since teachers and curriculum developers tend to focus on what is tested rather than on underlying learning goals (Binkley et al. 2012; Gardner et al. 2010; Harlen 2007). Teaching and assessment goals thus need to be aligned, and assessment methods need to be developed that allow for the assessment of inquiry competences within the different domains.

The aim of this chapter thus is to shed light on the understanding of inquiry and inquiry-based teaching and assessment within and across the different domains. The following describes the concepts, teaching and assessment of scientific inquiry, mathematical problem solving, design processes and innovation. For each domain, the description is structured along three major questions: (1) How is the concept defined and which competences are students supposed to develop? (2) What changes in teaching are needed to support students in developing these competences? (3) What changes in assessment are needed to assess these competences? The chapter concludes with a discussion about commonalities and differences with respect to the implementation of inquiry in the three domains and innovation, respectively.

The Concept of Scientific Inquiry

Scientific inquiry is not a uniformly defined concept. Within the science education literature, a general disagreement and variation can be observed with respect to the meaning of inquiry (e.g. Abd-El-Khalick et al. 2004; Anderson 2002, Furtak et al. 2012; Hmelo-Silver et al. 2007; Kirschner et al. 2006). From a holistic perspective, scientific inquiry could be described as a teaching and learning approach that tries to imitate more or less authentic scientific investigations embedded in real-world contexts. Learners are presented with problems and questions and supported in identifying ways of solving these problems by applying scientific thinking and working processes like planning an investigation or constructing models and by drawing on their knowledge of scientific content and the nature of science with the aim of constructing new knowledge.

Against this background, curricula, frameworks and reviews often describe scientific inquiry as a set of activities and the underlying competences that these activities require (e.g. Bell et al. 2010; Linn et al. 2004; National Research Council 2012; Pedaste et al. 2015). The findings from a recent review, however, ‘illustrate that the variability found in the research literature with respect to the definition and operationalisation of the holistic concept of scientific inquiry is also reflected at the level of single activities of the inquiry process’ (Rönnebeck et al. 2016, p. 190). Nevertheless, the curricula, frameworks and reviews are reflective of different phases and steps in the inquiry process and lead to models of scientific inquiry that encompass subject-specific competences like planning investigations as well as more generic competences like communicating (Pedaste et al. 2015; Rönnebeck et al. 2016; cf. Fig. 2.1). Moreover, the model by Rönnebeck et al. (2016) explicitly acknowledges the importance of relating scientific inquiry to scientific knowledge and knowledge about the nature of science and scientific inquiry.

Typically, scientific inquiry is regarded as a process (e.g. White and Frederiksen 1998; cf. Fig. 2.1). In this process, students apply the underlying competences in a sequence of steps that build on each other, e.g. they start with formulating a question and then generate a set of competing predictions and hypotheses related to that question. The advantage of this understanding of inquiry as a process is that students have to ‘reflect on both the limitations of what they have learned (which suggests new questions) and on the deficiencies in the inquiry process itself (which suggests how it could be improved)’ (White and Frederiksen 1998, p. 4). The improvement leads students back to the beginning of the process with a new or refined question or a revised approach.

Innovations on the level of learning goals imply innovations in teaching and learning approaches in order to address newly defined competences. One innovation that resulted from the emphasis on scientific inquiry is a change in the pedagogy from passive, teacher-led instruction to active, student-driven and cooperative learn-

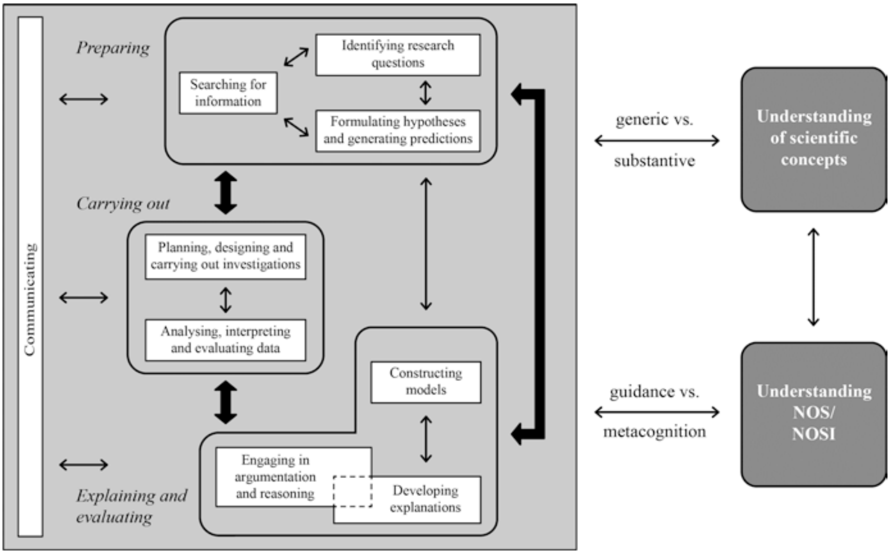


Fig. 2.1 The concept of scientific inquiry as a model (Rönnebeck et al. 2016, p. 189)

ing (Barron and Darling-Hammond 2008; Pellegrino and Hilton 2012). Thus, students should be engaged in actively building their knowledge (cf. Furtak et al. 2012), while the teachers make students' thinking visible, guide small group work and ask questions to enhance students' self-reflection. Possible methodological approaches to address these issues are the combination of different activities, the use of open-ended tasks, the implementation of scaffolding and the realisation of self-directed learning.

Basically, teachers initiate the inquiry process by providing opportunities 'that invite student questions by demonstrating a phenomenon or having students engage in an open investigation of objects, substances, or processes' (Kessler and Galvan 2007, p. 2). During the inquiry process, teachers act as facilitators providing guidance and scaffolds where needed. In general, minimally guided instruction isn't likely to support student learning – in order to be effective, inquiry-based instruction requires active guidance from the teacher (Hmelo-Silver et al. 2007; Kirschner et al. 2006). For example, 'teachers will likely have to modify student questions into ones that can be answered by students with the resources available, while being mindful of the curriculum' (Kessler and Galvan 2007, p. 2). However, the role of the teacher in inquiry teaching is much more complex than simply being a facilitator. Crawford (2000) identified ten roles a teacher takes up in inquiry classroom settings: motivator, diagnostician, guide, innovator, experimenter, researcher, modeller, mentor, collaborator and learner. Instead of the traditional distinction between the teacher as the knowledge giver and the students as the knowledge receivers, in inquiry settings, teachers and students 'collaborate to develop conceptual understandings through shared learning experiences' (Crawford 2000, p. 933).

By describing teachers' roles, it becomes obvious that doing inquiry in school inevitably differs from the work of real scientists. One aspect of these differences can be seen in practical reasons, e.g. available time and materials or safety precautions. A more important aspect, however, is described by the concept of educational reconstruction. Inquiry activities in instruction are related to specific, predefined learning goals and especially designed for students' learning and understanding. This focus differs from the focus in general science research although the underlying principles of the inquiry processes in both settings are the same (or at least very similar). Inquiry in schools thus requires the transformation of an authentic research situation into an educational setting – which might at times result in less authenticity (Furtak 2006; see also Chap. 1).

Nevertheless, when engaging in inquiry, students should be given 'the opportunity to undertake 'research activities' instead of just carrying out routine 'cookbook experiments'' (European Commission 2004, p. 125). Doing scientific inquiry should not only require students to engage in hands-on but also in minds-on activities by providing meaningful and realistic problems that allow for multiple solutions and multiple methods for reaching these solutions (Barron and Darling-Hammond 2008). In order to make the application of multiple methods for students possible, it is important to teach them the process of scientific inquiry as a sequence of interrelated steps as well as each step separately. By this the students learn a repertoire of different ways of how to do inquiry. Hadfield's (1995) example of the so-called copper problem (see box below) represents such a teaching and learning situation where students undertake research activities in the sense of scientific inquiry.

This focus on learning how to do inquiry is reflected in recent years in the USA where the discussion has moved away from using the term inquiry in favour of emphasising the importance of engaging students in *scientific practices* as the means to 'establish, extend and refine' knowledge (National Research Council 2012, p. 27). The eight practices described in the Framework for K-12 Science Education include (1) asking questions (for science) and defining problems (for engineering), (2) developing and using models, (3) planning and carrying out investigations, (4) analysing and interpreting data, (5) using mathematics and computational thinking, (6) constructing explanations (for science) and designing solutions (for engineering), (7) engaging in argument from evidence and (8) obtaining, evaluating and communicating information (National Research Council 2012, p. 42).

The definition of scientific inquiry by the description of related competences implies that teachers need assessment methods for each of the defined competences that help them detect if students reached the learning goals or not. However, Hume and Coll (2010) as well as Shavelson (2011) emphasise the difficulty of assessing inquiry-related competences. The former conclude that existing 'standards-based assessments using planning templates, exemplar assessment schedules and restricted opportunities for full investigations in different contexts tends to reduce student learning about experimental design to an exercise in 'following the rules'' (p. 43). Shavelson (2011) argues that the more complex the learning goals, the more difficult they are to measure. The understanding of competences as the ability to cope with complex challenges in everyday life means that assessment methods have to focus on scientific knowledge and on scientific inquiry.

Inquiry-Based Learning Example by Malcolm Hadfield (1995)

The copper problem. Students in small groups hold a small piece of copper foil in the Bunsen flame using a pair of tongs. When the copper is red hot, they place it on a ceramic mat and allow the copper to cool. Then, the students describe their observations. Afterwards, they formulate hypotheses about the observable black layer on the copper. Common hypotheses are that the black layer is soot from the Bunsen flame, that it forms out of the copper itself or that it has something to do with the ambient air.

In a next step, the students plan an investigation that tests their hypotheses. For example, they could think about experimental setups that isolate the copper from the flame or from the ambient air (see Fig. 2.2). Then, the students conduct the investigation and observe what happens. Based on their observations, they draw conclusions from their observations and evaluate their hypotheses.

In this example, the teacher intervenes relatively seldom. It is important that the students plan their inquiry on their own. The teacher's role is mainly to ensure that safety regulations are respected.

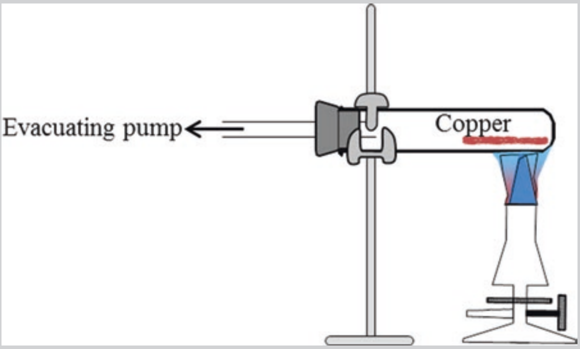


Fig. 2.2 Heating copper under conditions of a vacuum

In addition, the assessment methods should be related to everyday situations. Artificial tasks formulated as multiple choice test items can hardly measure inquiry-related competences. Usually, these items are used to assess students' understanding of scientific concepts. However, assessment methods should also focus on process-related aspects like students' competences in planning an investigation. Open-ended items or observations by the teacher seem to be more appropriate due to validity reasons. Compared to standards-based assessments, formative assessment has the great potential to address this issue of validity by focusing on process-related aspects (Barron and Darling-Hammond 2008; see also Chap. 3). Therefore, they are needed in addition to the above-mentioned standards-based assessments. The additional function of formative assessment is to give feedback to the students thus guiding their learning in the sense of scaffolding. Possible methods are rubrics, whole class discussions, performance assessments, written journals, portfolios, weekly reports and self-assessments (cf. Barron and Darling-Hammond 2008). It can be concluded that introducing scientific inquiry and formative assessment both require a considerable change in pedagogy (see also introduction of this book and Chap. 3 for details).

The Concept of Design Processes

As outlined in Chap. 1, competences in technology education link to its procedural nature, the core of which is design. This is recognised within technology education, 'Design is regarded by many as the core problem-solving process of technological development. It is as fundamental to technology as inquiry is to science' (International Technology Education Association 2007, p. 90), and also in science education, 'Technology as design is included in the [science] standards as parallel to science as inquiry' (National Research Council 1996, p. 24). In technology education, an inquiry approach involves presenting learners with challenges, problems and scenarios and supporting learners to identify ways of addressing these through iterative design processes that draw on critical thinking, creative and exploratory idea development and effective and thoughtful outcome resolution.

The early focus on design processes within technology education emerged in the late 1960s through a UK research project – the Design and Craft Education Project (Schools Council 1975). The project shifted the focus in what was a traditional *making* curriculum to *designing and making*, recognising that a design focus to teaching and learning enriched the subject greatly. The project was conducted at a time when design researchers were exploring professional design approaches, placing considerable attention on defining *the design process*. In the 1960s era of modernism, seeking the ultimate rational definition made sense and what emerged was a linear design process. This seemed like a logical sequence – identify a problem, conduct research, generate ideas, make a solution and evaluate its effectiveness. The stages in the process became a focus for teaching and, more significantly, for assessment with marks being allocated to each stage, creating what was, effectively, an early version of competences in technology education. The approach was embedded in a formal external examination for 16-year-olds (NWSEB 1970) and quickly spread to other assessment systems.

However logical a linear process may seem, it is more a management process than a representation of how designing takes place. The suggestion that a person somehow restrains from having any ideas until a *problem* is fully defined and all research is undertaken makes no sense – even if it was possible to prevent ideas from beginning to form. The notion that no evaluation needs to take place until the

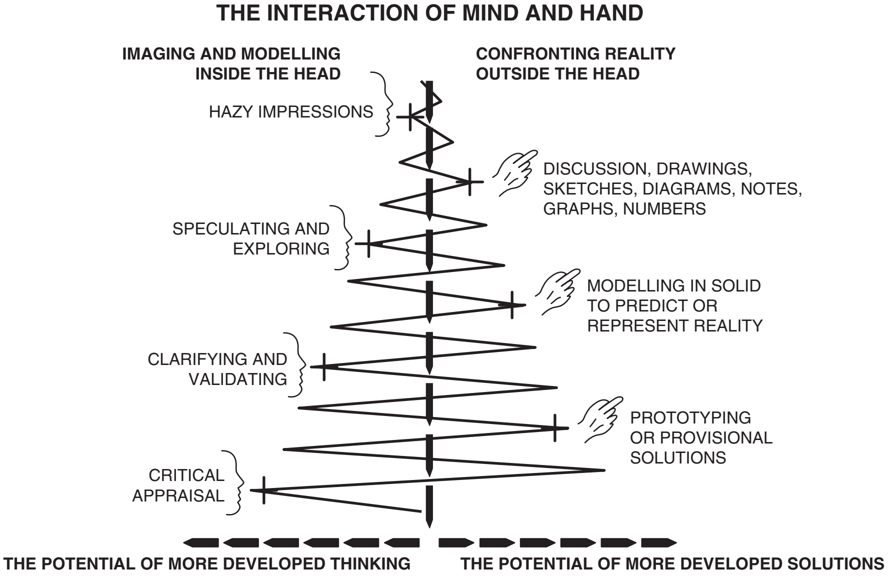


Fig. 2.3 The APU D&T model of iterative design (Kimbell et al. 1991, p. 20)

project is completed also makes no sense. Dissatisfaction with a linear model of the design process emerged both in the professional design world and in educational contexts. Addressing this dissatisfaction was an early challenge for a major research project commissioned to assess the design and technological capability of 15-year-olds in England, Wales and Northern Ireland (the APU D&T project, Kimbell et al. 1991). Drawing on the team's experience as design and technologists and teachers and on early empirical fieldwork, an alternative model was created (see Fig. 2.3). As its starting point, it took the spark of a hazy idea in the mind's eye, possibly provoked by a problem, maybe by an opportunity. The process was then a journey of taking action to develop the idea and iterating this with reflection, appraising developments to identify next steps, to-ing and fro-ing until a thoughtful, well-developed outcome was created. The iterative nature of the process was critical – action needed to be taken on the hazy internal idea to bring it out into the world by drawing, talking about it and modelling it in some way. In turn, the action provided models to reflect on, speculating on how it might develop, what information was needed to take it forward and so on.

The research team used the model as a framework for structuring and assessing design and technological capability (Kelly et al. 1987). The sample of learners generated samples of design and technology work that were initially assessed holistically and then analysed to identify qualities of performance. Holistic assessment allowed assessors to see the overarching qualities of the work, and analysis provided empirical evidence of the qualities within the work. Key attributes and competences became apparent through a combination of the two. Three clusters of procedural capability were identified: reflective qualities, active qualities and appraisal qualities that linked the two together. The holistic assessment revealed the extent to which high-quality performance was directly linked to the ability to iterate between action and reflection throughout the activity. It underscored the critical importance of an iterative process, a factor that was echoed by the national working party developing the first English/Welsh National Curriculum who stated that 'because Design and Technology activity is so integrative, the approach to the assessment of learners' performance in this area should ideally be holistic' (DES/WO 1988, para 1.30). Evidence of design iteration contributing to high levels of performance has been found in other projects, including recent research (Botleng et al. 2016; Crismond 2011; Strimel 2015).

Two research projects building on the APU D&T project clarified further detail. The Understanding Technological Approaches project (1992–1994) observed and documented in fine detail 80 live projects across ages ranging from 5 to 16. The project focused on the *in the moment* design and technological intentions of learners and how these were manifested (Kimbell et al. 1996). It identified the following facets of performance common across all age groups: investigating, planning, modelling and making, raising and tackling design issues, evaluating, extending knowledge and skills, and communicating. The Assessing Design Innovation project was commissioned to research ways of introducing creativity and innovation into high-stakes assessment projects (Kimbell et al. 2004). The research identified further elements of idea development – into the *having*, *growing* and *critiquing* of ideas within an iterative process. Once again, the interaction of these throughout a project was revealed through holistic assessment. Atkinson (1999) suggests that a holistic experience allows learners to understand how component parts of the process link together.

Iterative processes of design are now central in the English national curriculum, including in high-stakes assessment. The critique of linear processes and the shift to cyclical and iterative processes of design can be commonly seen in curriculum documentation in other settings (e.g. Department of Basic Education 2011; International Technology Education Association 2007; Ministry of Education 2010). In the USA, the International Technology Education Association (ITEA) Standards for Technological Literacy highlight an iterative process focusing specifically within engineering design. For them this is an important step to move away from a historic craft tradition and towards a stronger link with engineering futures, both in the work place, indicating a more instrumental ambition, and through a more general engineering literacy (International Technology Education Association 2007; Lewis and Zuga 2005). While engineering is being aligned with technology education in many national contexts, an engineering design process has a more narrow focus, engineering being but one of many significant contributions made through design.

Across technology education, there is relative agreement regarding the individual qualities that contribute to technological literacy and/or capability, such as addressing task and user needs, investigating, modelling ideas, applying and acquiring knowledge and skills and critiquing idea development. Furthermore, there is the fundamental ability of using the individual qualities in a responsive and integrated way through an iterative process and, as identified in Chap. 1, doing this within a societal context. Taken together, this repertoire of individual and integrative qualities is the challenge and focus of learning, teaching and assessment.

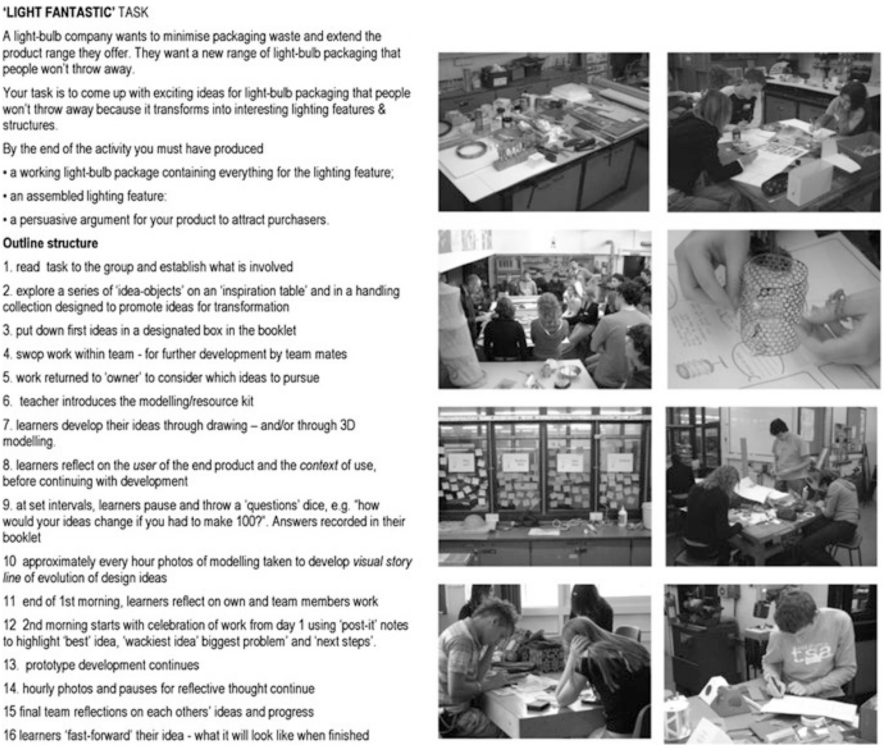
Technology teachers are generally comfortable with a project-based approach to learning and teaching, but manageability of time, resources and class sizes often leads to prescriptive projects that are dominated by teaching of knowledge and skills rather than being genuinely design led and based in socially and culturally relevant contexts. Reports in England have identified that, at worst, design and technology teaching can be too formulaic, too narrowly focused with projects that lack challenge and often result in unfinished outcomes. But they also identified that, at best, teachers have high expectations, set challenging and ambitious projects in relevant contexts that spark the learners' imaginations and create palpable excitement in the learning (Department for Education 2011; Design Commission 2011; Miller 2011; Ofsted 2011, 2012).

The importance of authenticity in project-based learning has been highlighted within and beyond technology education (e.g. Barak and Awad 2008; Merrill et al. 2010; Snape and Fox-Turnbull 2013, Stables 2013; Turnbull 2002). A major challenge for teachers is structuring and scaffolding projects that are set in authentic contexts that allow learners to take ownership of tasks. A broad and loosely defined context provides opportunities for ownership, but learners can get lost in the complexity and overwhelmed by a perceived enormity of the challenge. If it is too tightly specified, on the other hand, there may be oversimplification and too little room for personalisation (Jones 1997; Kimbell et al. 1991). A framework was created through the APU D&T project that identified levels of complexity and hierarchy in tasks from open contexts, to referenced scenarios, to specific briefs. The framework allows teachers to place a design challenge at an appropriate level for learners and then create the scaffolding to enable learners to move between the levels, keeping sight of the broader context and their own specific challenge (Kimbell et al. 1991; Kimbell and Stables 2007).

Barak and Awad (2008) provide insights into learners choosing of authentic tasks from within their own personal contexts, based on an area of specified challenge, for example, the creation of an information system, highlighting the motivational aspects of enabling personalisation in choices made. Snape and Fox-Turnbull (2013) also stress the importance of learner motivation in authentic tasks, seeing learner engagement as a dimension of the interweaving of elements of curriculum, suggesting that 'in order to elucidate authentic technological practice the dimensions of authenticity are woven together by rich contexts, social construction, meaningful connections and student engagement' (p. 60). They (along with others) also point to the value of a socio-constructivist approach through which knowledge is developed through social experience and collaboration and emphasise the value of a cognitive apprenticeship model. Moreland et al. (2008) regard teachers working alongside learners, modelling thinking and designing, as a valuable approach to support learning while providing feedback. Drawing attention to the requirements of supporting diverse projects and the resulting diverse learning needs these produce, Snape and Fox-Turnbull (2013) suggest that learner action plans enable teachers to manage a balance between *just in case* and *just in time* teaching.

To support metacognitive learning, documention and reflection are an important dimension of project-based learning. A curriculum-led assessment approach supports the dual value of making learning visible, both for the learner and the teacher, providing important insights for formative assessment. The use of project portfolios is ubiquitous in technology education. Portfolios based on selections of work are useful to help learners curate the documentation of their learning, but these *after-the-event*, container style portfolios have been critiqued for becoming products in their own right and acting as either a distraction for or displacement of learning, presenting ritualistic, prettied up documentation rather than the thought of an action as it took place. Mike Ive, former Chief HMI for design and technology in the UK, repeatedly referred to this as *neat nonsense*, reporting formally that 'many [learners] still spend too much time on superfluous decoration of their design folders rather than on real design development' (Ofsted 2002, p.4). McLaren (2007) suggests that this has resulted in assessment that fails to authentically model design processes hence resulting in the production of artificial documenting that demotivates learners.

An alternative to an *after-the-event* portfolio is a working portfolio where documentation is captured dynamically in real time as a project progresses. Spendlove and Hopper (2006) see working portfolios as liberating learners, opening up possibilities for creative dialogue. Digital tools used in e-portfolios have enabled this in a literal sense, building audio and video tools into portfolios in ways that provide opportunities to capture the learner's voice. The e-scape project (e-solutions for creative assessment in portfolio environments, Kimbell et al. 2009) explored this potential, by creating a web-based application that allowed teachers to structure learning activities through which learners documented their project work in real time, using a collection of digital tools including text, drawing, mind mapping, photo, audio and video, thus creating a 'trace of the thinking left behind' (Kimbell and Stables 2007, p. 222). Moreland et al. (2008) suggest that design and technology is an ideal place to exploit such multimodal approaches for assessment. Using digital tools has been found to support assessment for different learning styles, including learners with special educational needs (Stables et al. 2015). The e-scape system includes possibilities for peer assessment via text and drawing, using the concept of *critical friends*, thus also supporting collaboration. A linked project extended the initial range by adding an option for teachers to add formative feedback into the portfolios, including while the learners were working, 'comments/suggestions/ideas in exactly the way one would if talking directly to learners in the classroom' (McLaren 2012, p. 234). A further development currently being researched is the possibility of a built-in screen avatar taking a critical friend role (Stables et al. 2016). The assessment potential of e-portfolios has been exploited by examination boards enabling the submission of portfolios in digital format, often using an application such as Microsoft PowerPoint. The e-scape portfolio, being web-based, allowed for a further innovation through the use of adaptive comparative judgement that not only created high levels of reliability in assessment but also acted as a professional development tool for those engaged in the assessment process (Kimbell 2012; Pollitt 2012; McLaren 2012). It also enabled peer assessment,



'LIGHT FANTASTIC' TASK

A light-bulb company wants to minimise packaging waste and extend the product range they offer. They want a new range of light-bulb packaging that people won't throw away.

Your task is to come up with exciting ideas for light-bulb packaging that people won't throw away because it transforms into interesting lighting features & structures.

By the end of the activity you must have produced

- a working light-bulb package containing everything for the lighting feature;
- an assembled lighting feature:
- a persuasive argument for your product to attract purchasers.

Outline structure

1. read task to the group and establish what is involved
2. explore a series of 'idea-objects' on an 'inspiration table' and in a handling collection designed to promote ideas for transformation
3. put down first ideas in a designated box in the booklet
4. swop work within team - for further development by team mates
5. work returned to 'owner' to consider which ideas to pursue
6. teacher introduces the modelling/resource kit
7. learners develop their ideas through drawing – and/or through 3D modelling.
8. learners reflect on the *user* of the end product and the *context* of use, before continuing with development
9. at set intervals, learners pause and throw a 'questions' dice, e.g. "how would your ideas change if you had to make 100?". Answers recorded in their booklet
10. approximately every hour photos of modelling taken to develop *visual story line* of evolution of design ideas
11. end of 1st morning, learners reflect on own and team members work
12. 2nd morning starts with celebration of work from day 1 using 'post-it' notes to highlight 'best' idea, 'wackiest idea' biggest problem' and 'next steps'.
13. prototype development continues
14. hourly photos and pauses for reflective thought continue
15. final team reflections on each others' ideas and progress
16. learners 'fast-forward' their idea - what it will look like when finished

Fig. 2.4 The structure of a *controlled assessment* iterative design assessment task from the Assessing Design Innovation project

explored in a small trial with 15-year-olds (Kimbell et al. 2009) and more extensively with undergraduate design students who found that it had 'the potential to increase thinking, learning and confidence, helping the student to establish the role and purpose of assessment' (Seery et al. 2012, p. 209).

Through the Assessing Design Innovation project, a structured design and technology assessment task framework was created, undertaken as *controlled assessment* (Isaacs 2010). An example of this is given here to illustrate how the task was structured (Fig. 2.4). The task was designed to take 6 h, ideally conducted over two consecutive mornings.

The Concept of Problem Solving

In Chap. 1 we considered the requirement within mathematical literacy to solve mathematical problems and contrasted those where the outcomes are validated within mathematics (sometimes referred to as investigations) and those where the validation came from outside the field of mathematics (mathematical modelling). Defining inquiry-based education (IBE) or inquiry-based learning (IBL) as a concept within mathematics education is relatively new and often associated with EU-funded projects (Maaß and Doorman 2013). In describing the rationale for the PRIMAS project, Maaß and Doorman (2013) define it as ‘refer[ing] to a teaching culture and to classroom practices in which students inquire and pose questions, explore and evaluate’ (p. 887). The nature and purpose of the problems-to-be-solved and how solutions might be validated poses significant issues for the competences that could be developed. Maaß and Doorman suggest IBE can support ‘develop[ing] competences in such areas as attaining new knowledge, creative problem solving and critical thinking’ (ibid, p.1). Alongside PRIMAS, the Fibonacci project aimed to ‘contribute to the dissemination of IBL by designing, implementing, and evaluating a dissemination process’ (Maaß and Artigue 2013, p. 788). This consisted of local and regional centres together with community involvement and an emphasis on collaboratively produced materials with attention on the diversity of contexts found in different centres.

The Danish KOM curriculum reform project roots new syllabus construction in mathematical competences. These seek to elaborate the competences involved in asking and answering questions (mathematical thinking/problem tackling/modelling/reasoning) and in mathematical language and tools (representing/symbol and formalism/communicating/aids and tools) (Niss and Højgaard 2011). The ordering seems significant in that asking and answering questions is made possible through the deployment of mathematical tools and language. It is notable that competences are required to both ask and answer questions in the sense of problems to be solved. So, the learner is involved in an engagement with the generation of the problem, and a clear distinction is made between problems within mathematics and those where mathematics is deployed in settings outside of mathematics. These are described as problem tackling and modelling, respectively. However, the notion that modelling is simply one of the eight competences above is critiqued by Niss himself who suggests that ‘the entire domain of mathematical competencies must be perceived as a proper subset of the modelling competency’ (Niss 2015, p. 2). This suggests that the totality of mathematics education is directed at problem solving (and posing) and that modelling is required to achieve this. IBE meanwhile presents a possible mechanism for achieving it. The description of the KOM project does not even contain the word *inquiry*, but the centrality of student activity in *investigation* and *modelling* occurs repeatedly, suggesting these terms describe a pedagogy comparable to IBE (Niss and Højgaard 2011).

In contrast, the PISA 2012 framework states that ‘mathematical literacy is assessed in the context of a challenge or problem that arises in the real world’ (OECD 2014, p. 37). This represents a more limited setting for mathematical problem solving, resonant with our initial notion of modelling, but not the overarching definition suggested by Niss, which would include problems within mathematics or investigations. Burke et al. (2016) propose a structuring of mathematical modelling practices enabling an analysis of practices such as those described above, when deployed as educational activities. This uses Dowling’s notion of discursive saturation which determines the extent to which the principles of an activity can be determined in discursive forms (Dowling 2007). Where, for example, mathematics

Table 2.1 Four characterisations of mathematical modelling practice

Quantification rule (external syntax)	Mapping rule (internal syntax)	
	DS+	DS−
Ds+	Definitive mathematisation	Ad hoc mathematisation
Ds−	Derived mathematisation	Originative mathematisation

practices in general are highly discursively saturated, in that statements made within mathematics are very clearly determined by the language and syntax of mathematics, by contrast swimming is not generally available in discursive forms, and there is a weaker relationship between descriptions of it and the practice itself. Mathematical modelling requires an internal syntax in which mathematical terms and statements may be clearly constructed and amenable to proof (high discursive saturation/DS+). This is referred to as a mapping rule. It also requires an external syntax in which statements from the originating context can be clearly quantified and thus engaged with using the mathematics. This is the quantification rule. This establishes four characterisations of mathematical modelling practice (Burke et al. 2016, p. 4–5) as shown in Table 2.1.

The pedagogic aim of engaging with mathematical modelling would be to apprentice learners into a practice of definitive mathematisation. Yet, this mode is almost never present in problems used in the PISA tests. Either the problem fails to establish clarity internally or externally, making the practice ad hoc, or it establishes clarity within mathematics but no credible rules for quantifying data from the *real-world* setting. In maths textbooks this is commonplace with context-based exercise problems (Burke et al. 2016, p. 5–6). The setting of problems in an apparently real-world context and the requirement for a solution determined using some mathematical principles do not in itself provide a pedagogic activity in mathematical modelling/problem solving.

As described earlier, the PRIMAS project refers to a teaching culture which is supportive of student inquiry. In Chap. 1, we have suggested that the nature of the problem to be solved determines the nature of the problem solving process and hence the competences that can be developed though engagement with them. Thus, teacher practice is central to the possibility for inquiry. An important contribution to inquiry-based learning in mathematics was the CAME project in the UK started in 1993. This was built around the deployment of 30 *thinking maths* activities, with a strong emphasis on discussion, pair and group work and student presentation. Notably, there was a very strong element of teacher professional development. Shayer and Adhami (2007) in their post project retrospective state that:

> The mathematics teachers were encouraged, as part of their PD, to establish connections between the agenda of the CAME lessons, and the contexts of their ordinary mathematics lessons using the same reasoning patterns. […] In effect many of them were taking a ‘Thinking Maths’ approach into all their teaching, and by implication encouraging their students to take a thinking approach to their learning, which seems to have affected their learning in other subjects as well (Shayer and Adhami 2007, pp. 287–88).

A core element of the pedagogy, which they have developed from the inquiry-based learning and thus brought into their general teaching, is exemplified thus:

> At this point the teacher, rather than spending time going round to groups 'helping' instead listens, sees and notes where each group has got to, and, depending on the different aspects of working on the underlying mathematical ideas he finds, makes a plan of which groups, and in what order, he will ask to contribute to Act 3. He may occasionally throw in a strategic question if he sees a group is stuck (ibid, p. 275).

This is strongly resonant with the principles set out for assessment for learning initiated by Black and colleagues at the same institution (Black et al. 2004). Maaß and Doorman (2013) describe the teacher's role in PRIMAS: 'Teachers are proactive: they support pupils who are struggling and challenge those who are succeeding through the use of carefully chosen strategic questions' (p. 887). This intense multilayered approach was also the expectation with CAME. This is clearly complex and thus expensive, but the hope for student competences is also complex and as we have seen requires sophisticated task design and teaching to enable leaners to be apprenticed into the definitive mathematisations required for mathematical modelling and thus real-world problem solving, as in the example below.

Intriguingly, the teachers' beliefs of the nature of mathematics in itself seem to have an effect on their students' measured school mathematics achievement. Askew et al. (1997), studying primary school teachers' practice in the Effective Teachers of Numeracy project in the UK, reported that teachers who believed that mathematics was a multiply interconnected subject (referred to as *connectionist*) were most effective in terms of the student outcomes they supported. This is understood through the pedagogy that this thinking enabled: 'The connectionist teachers' lessons were generally characterised by a high degree of focused discussion between teacher and whole class, teacher and groups of pupils, teacher and individual pupils and between pupils themselves' (ibid, p. 46).

We have seen that PISA test practices do not incorporate all aspects of real-world problem solving despite a strong urge to do so. In Denmark, a wide ranging curriculum reform allows the possibility for corresponding developments in assessment systems. There is considerable discussion of the varied nature of an assessment system that would support the new competence-based syllabus, both new and old: 'However, there is still a great need for continuously devising, testing and new developments evaluating new test and examination forms' (Niss and Højgaard 2011, p. 144). However, the outcomes of the CAME project and the Effective Teachers of Numeracy project suggest that intense and long-term intervention in teacher development in inquiry-based learning has the potential to produce significant gains in students' general mathematical performance. In the PRIMAS and ASSIST-ME projects, there is a desire for change in assessment systems; however, there appear to be benefits from the inquiry-based approach developed in these projects even within existing systems.

Inquiry-Based Learning Example from the Assist-Me Project (http://assistme.ku.dk)

The Towers of Hanoi. Students in small groups solve this classic wooden puzzle, to move piles of different-sized discs from the one end of three pegs to the other end peg one at a time, never placing a larger disc on a smaller one (Fig. 2.5).

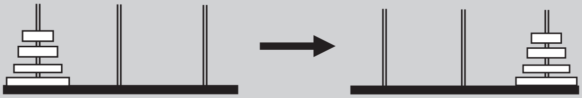


Fig. 2.5 The Towers of Hanoi

When successful they repeat the tasks sufficiently often that they can do this reliably and feel confident they have minimised the number of moves for a given number of discs. They capture the moves in diagrammatic/symbolic/textual form to report their *method*. They vary the number of discs looking for relationships between the number of discs and the minimum number of moves as a direct relation and as a recurrence relation. They look to explain why the direct relation must always hold true and generate embryonic proofs (potentially by induction). The teacher intervention is as characterised in the reports from CAME and PRIMAS, with small group work, focused discussion and student presentation. The teacher does not hint towards an outcome, but prompts for a process to continue. This generates competences *within* mathematics as described in the KOM project and is an example of a definitive mathematisation as a mathematical modelling practice, since the internal syntax generates a definitive proof and the relationship between the real-world (wooden puzzle) setting and its quantification (number of moves) is very clearly described.

The Concept of Innovation Competence

In Chap. 1, it was argued that one of the focal competences of the twenty-first-century skills programme is innovation competence. In this context, teaching for innovation is understood as mono- or interdisciplinary teaching activities in which students work on using their disciplinary knowledge and skills in order to improve on an authentic *field of practice*. Here, field of practice is meant in the broadest possible sense as ranging from the performance of very specific activities such as the practice of showering in the morning to complex clusters of activities such as the practice of getting rid of waste at music festivals. The previous chapter also described that innovation competence can be operationalised as students' ability (alone or in collaboration with others) to (a) generate solutions to issues while drawing on their disciplinary knowledge and their analysis of the field of practice where the issue arises, (b) analyse and reflect on the value-creating potential and realisability of their ideas, (c) work towards implementing their ideas and (d) communicate about their ideas to various stakeholders (cf. Nielsen and Holmegaard 2015). As a learning goal, innovation competence involves five dimensions: creativity, collaboration, (disciplinary) navigation, implementation and communication. Each dimension is described in Chap. 1.

In teaching for innovation, there is no theoretically correct answer to the tasks the students are doing, and the teacher is not the disciplinary expert who knows the way to solve the problem or do the task. Thus the teacher's role is as a supervisor, facilitator or guide very similar to the teacher's role in inquiry teaching. Indeed, similar to inquiry teaching, teaching for innovation shifts the focus of formative assessment in comparison to regular mono-disciplinary teaching. Innovation competence is very much a process competence. Therefore, the formative assessment should be directed at facilitating that students become more able to work in specific processes, rather than facilitating that students master a specific disciplinary content (e.g. Harlen 1999). Figure 2.6 shows one kind of model (the double diamond model) that can capture archetypical innovation work processes. The Polluted Seawater task provides an example of a comprehensive activity that roughly follows the double diamond model.

As argued in Chap. 1, innovation competence can be seen as a complex of five dimensions. This division can help teachers and educators to operationalise the competence for designing prospective activities and assess students' competence development formatively and summatively. A generic way of spelling out the five dimensions would be the following (a richer description was developed in Nielsen 2015a):

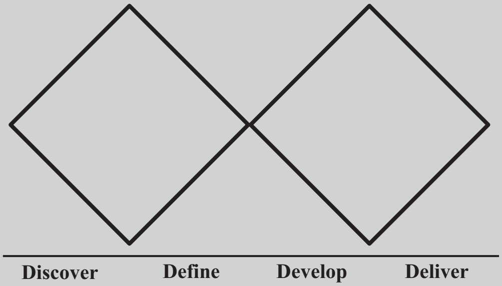
- Creativity:
  - The student independently finds or independently interprets a given problem issue from a field of practice.
  - The student generates a range of ideas or solutions to a problem rather than just one idiosyncratic type of idea.
  - The student works with generated ideas in a critical fashion, e.g. by evaluating, sorting, revising and expanding the ideas of herself or others.
- Collaboration:
  - The student takes responsibility for and facilitates that the collaborative group finishes its tasks, e.g. by being able to identify how the competences of the people in the group can complement each other.
  - The student includes others and is flexible in a collaboration, e.g. by being able to work with many different types of stakeholder or people, rather than just a limited number of people or classmates.
- Navigation:
  - The student interprets a specific problem from practice as a problem that can be approached from a disciplinary perspective, e.g. by being able to translate the problem into disciplinary language.

  - The student functionally handles knowledge, e.g. by handling plentiful and heterogeneous information and sorting and prioritising which information is the most important to go into detail with.
  - The student masters complex work processes.
- Implementation:
  - The student makes informed decisions about what actions to take in a specific time in a work process.
  - The student takes action outside his/her comfort zone (e.g. by seeking information outside the classroom).
  - The student takes risks and puts him/herself and others into play, e.g. by not stopping at the level of an idea but carrying out that idea.

The Double Diamond Model

This model, constructed by the Design Council (2005), can be seen as representative of typical teaching activities that aim to foster all five dimensions of innovation competence (the original model is more focused on design processes). In the *Discover* phase, students make inquiries into the field of practice that they are working on with the aim of identifying factors and aspects of the specific problem. In teaching for innovation, this will involve inquiries into the relevant disciplinary subject areas as well as information relevant to the field of practice and its stakeholders, for example, information about what leads to the specific problem or how the problem is currently handled in the field of practice. In the *Define* phase, students converge on a focal factor or aspect that they would like to improve; here the aim is to delimit the problem area and define possible success criteria for improvement. In the *Develop* phase, students generate ideas for improving the delimited problem. This may involve multiple cycles of generating, testing and revising ideas (and possibly prototypes). In the *Deliver* phase, the proposed solution is finalised and handed over to the field of practice, typically by communicating an idea or presenting a prototype to relevant stakeholders (a number of other similar models for designing teaching for innovation are available at https://innovationenglish.sites.ku.dk).

Fig. 2.6 The double diamond model



- Communication:
  - The student assesses how to communicate (e.g. to stakeholders) in a given situation.
  - The student masters a range of communication techniques and genres.
  - The student communicates in an engaging and convincing manner.

Students can acquire competences and skills relevant for innovation in different degrees of comprehensiveness. It is entirely possible for a teacher to focus on one or two of the dimensions of innovation competence. In a recent Danish attempt to trial examination formats for innovation competence (Nielsen 2015b), teachers elected to have some activities cover all five dimensions, while other activities strategically focused on one or more dimensions. For example, one could imagine a class working intensively on developing the collaboration dimension by working in groups on some interdisciplinary content under the observation of the different teachers involved, with pauses in the group work where the teachers, based on their observations, can provide formative feedback to individual students on how they have observed the students' collaboration skills and provide improvement strategies for them.

Innovation-Oriented Learning Example

Polluted Seawater. The project is started by a marine biologist from the municipality who introduces the students to a problem related to seawater quality. Students work in groups experimentally and/or by means of data processing to investigate/document the problem, its cause and its extent. The groups must generate possible solutions to improve the seawater quality and discuss their practical realisability, benefits and consequences. The end product is a proposed solution from each group which is communicated (e.g. as a poster exhibit) to the marine biologist.

This activity is divided into two main phases:

Phase 1 (Biological inquiry): Inquiry process of possible causes to the problem. This phase could include measurement of nitrate (or phosphate) and *E. coli* concentration in water samples from selected sites (rivers and sea) possibly before and after rain, constructing plots for biochemical oxygen demand (BOD5) for selected streams of water into the sea and identifying experts and authorities who can provide knowledge and inspiration; the marine biologist can also be contacted if groups need more information or have questions about the local conditions.

Phase 2 (Generating solutions): The groups work on ideas for possible solutions. The task is to narrow in on the possible causes that each group wants to work with, in order to target the proposed solutions. This phase resembles an inquiry process, but aims to identify viable solutions to the issue and testing of or reflection on their realisability and potential for value creation.

Summary and Discussion

In the last decades, inquiry, or as it is more recently described, engaging students in scientific practices, has become a fundamental approach in science teaching and learning (National Research Council 1996, 2012). Its importance has been mirrored at the European level in the funding of several EU projects (e.g. S-TEAM, ESTABLISH and PRIMAS) aiming to support science teachers in implementing the approach. Despite its prominent role in science education research, however, no general agreement about the exact definition of scientific inquiry exists. From a holistic perspective, inquiry-based approaches to science teaching and learning generally try to imitate more or less authentic scientific investigations embedded in real-world contexts. They involve presenting learners with problems and questions and supporting them in identifying ways of solving these problems by applying the thinking and working processes of scientists and by drawing on their knowledge of scientific content and the nature of science with the aim of constructing new knowledge.

Looking at inquiry-based approaches across the domains of science, technology and mathematics, the concept seems to be strongly related to the field of science education (Ropohl et al. 2013). In mathematics and technology education similar concepts exist; however, they usually go under different names. In mathematics education inquiry is manifested in two different ways: firstly learners exploring mathematical problems, developing their own mathematics and working towards solutions and their proof or secondly learners using techniques of mathematical modelling to support elements in the process of solving problems originating from outside of mathematics. A clear distinction thus exists between those problems where problem and solution reside within mathematics and those where the problem originates outside of mathematics, the latter necessarily being examples of mathematical modelling. This approach has been referred to as problem-based learning which ‘describes a learning environment where problems drive the learning’ (Rocard et al. 2007, p. 9). A significant difference with scientific inquiry is the focus on the mathematical development towards deduction and proof, often with a corresponding lack of interest in the actual problem resolution, where the solution ‘is presented as a deduction from what was given in the problem to what was to be found or proved’ (Schoenfeld and Kilpatrick 2013, p. 908). In technology education, the closest connection to inquiry is provided by approaches to teaching and learning using the concept of design processes. Inquiry in technology education involves presenting learners with challenges, problems and scenarios and supporting learners to identify ways of addressing these through iterative design processes that draw on critical thinking, creative and exploratory idea development and effective and thoughtful outcome resolution. Scientific inquiry and design processes are closely related – Lewis (2006) even proposes that ‘design and inquiry are conceptual parallels’ (p. 255) since they converge on many dimensions like, e.g. they are both reasoning processes including elements of uncertainty and the need for testing, evaluating and decision making, they both depend on content knowledge and they both work under domain-specific constraints. The major distinguishing characteristic is a difference in purpose. Whereas pure science is inherently speculative, the purpose of technology is invariably instrumental: 'The goal of science is to understand the natural world, and the goal of technology is to make modifications in the world to meet human needs' (National Research Council 1996, p. 24; also Lewis 2006).

One of the focal competences of the twenty-first-century skills programme is innovation competence. In the case of teaching for innovation, inquiry involves presenting learners with real-world problems and supporting them to identify realisable and value-generating solutions to these problems through iterative processes that draw on idea generation, disciplinary navigation, collaboration, implementation and communication. Obviously scientific inquiry, design processes and teaching for innovation have a number of similarities. However, teaching for innovation differs significantly from inquiry teaching in science because the former always begins with a problem from an authentic field of practice in the real world that students work to solve or alleviate – there is so to speak always a user (a person in the field of practice) who is the main addressee of the students' work. This is not necessarily the case in scientific inquiry teaching. Teaching for innovation also differs from design processes in the sense that the latter is typically taught in a specific discipline, design, engineering or technology. Teaching for innovation does not fall under the purview of a specific discipline but is a possible extension of every existing discipline.

Despite these domain-specific differences in the understanding of inquiry, however, inquiry-based teaching and learning shares characteristics across domains that could be factored in a kind of *meta-definition* of inquiry: Scientific inquiry in science, problem solving in mathematics, design processes in technology and innovation as a cross-curricular approach all require students to become actively engaged in solving problems of a personal, societal, environmental or disciplinary nature by drawing on their disciplinary knowledge which involves both, knowledge about the content and the nature of their discipline, and by applying the domain-specific and generic thinking and working processes of scientists. As already mentioned in Chap. 1, this overarching understanding of inquiry across domains stresses again that competences and knowledge are always intertwined. Acting competently inevitably requires knowledge – the specific amount and type of knowledge that is necessary to solve a problem, however, may vary depending on the specific context in which the problem is embedded and the specific task that students are facing (see Chap. 1; Rönnebeck et al. 2016).

By involving students in inquiry processes or scientific practices, teachers can address complex subject-specific (e.g. carrying out investigations in science or designing a device addressing a specific need in technology) as well as more generic competences (e.g. developing explanations or arguments based on evidence or communicating efficiently). The role of the teacher thereby changes from primarily being the disciplinary expert and conveyor of knowledge to becoming a facilitator who guides the students through their learning providing disciplinary knowledge when needed.

In order to do this, the teacher takes on multiple roles like motivator, diagnostician and guide but also as collaborator, mentor, modeller and learner (Crawford 2000). In a similar way, the role of the students changes. Instead of being mere passive recipients of instruction, they need to become active participants in their learning processes. In inquiry settings, the traditional distinction between the teacher as the knowledge giver and the student as the knowledge receiver is replaced by the teacher working collaboratively with his or her students in order to construct understanding. To effectively support students' learning in inquiry settings, teachers need to actively guide their students through the inquiry process by creating opportunities to learn, encouraging students to become active learners and providing scaffolds and support when needed. Taking on this multitude of roles is demanding for the teacher and requires a high level of expertise, a great level of involvement and a willingness 'to embrace inquiry as a content and pedagogy' (Crawford 2000, p. 933).

New learning goals moreover require new forms of assessment that allow for the assessment of complex, process-oriented competences and acknowledge the active role of the students (see also Chaps. 1 and 3). Across all domains, developing and implementing such assessments, whether for formative or summative purposes, is a complex and challenging task. The challenges that researchers, teacher educators and teachers face include reaching a shared understanding of the learning goals and competence expectations, defining what counts as evidence of achievement as well as ensuring reliability and validity (see also Chaps. 1 and 3). Against this background, formative assessment could offer promising perspectives because of its inherent emphasis of active student engagement and its potential for supporting complex learning processes by defining learning goals and competence expectations and by providing feedback to students on that basis. Examples of formative assessment methods used to assess inquiry competences in the different domains will be presented in the following chapters.

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