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Engineering design in the primary school: applying stem concepts to build an optical instrument

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ABSTRACT

Internationally there is a need for research that focuses on STEM (Science, Technology, Engineering and Mathematics) education to equip students with the skills needed for a rapidly changing future. One way to do this is through designing engineering activities that reflect real-world problems and contextualise students' learning of STEM concepts. As such, this study examined the learning that occurred when fifth-grade students completed an optical engineering activity using an iterative engineering design model. Through a qualitative methodology using a case study design, we analysed multiple data sources including students' design sketches from eight focus groups. Three key findings emerged: first, the collaborative process of the first design sketch enabled students to apply core STEM concepts to model construction; second, during the construction stage students used experimentation for the positioning of lenses, mirrors and tubes resulting in a simpler 'working' model; and third, the redesign process enabled students to apply structural changes to their design. The engineering design model was useful for structuring stages of design, construction and redesign; however, we suggest a more flexible approach for advanced applications of STEM concepts in the future.

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Introduction

Recently there have been calls for a focus on STEM (Science, Technology, Engineering and Mathematics) education to prepare students with the appropriate skills required for a rapidly changing society where creative and competent STEM professionals will be needed (National Research Council [NRC], 2014; Office of the Chief Scientist, 2014). STEM skills underpin emerging knowledge-based industries such as biotechnology, information and communication technologies (ICTs) and futuristic sustainable technologies, as well as providing a competitive advantage to established industries such as medical research, agriculture and mining (Office of the Chief Scientist, 2014). Building such skills is the goal of many nations striving to advance research and development through the growth of innovative technological solutions (National Research Council, 2009). As such, we need to equip students with the STEM skills required by adopting new approaches to teaching and learning across the STEM disciplines especially in the earliest

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grades (National Research Council, 2009; Office of the Chief Scientist, 2013, 2014). The need to target STEM education in the primary schools is further evident in research showing that the average age of initial interest in STEM is 8.2 years (Harris, 2011), but by 8th grade almost 50% of students have lost interest in STEM subjects (Murphy, 2011).

In the past, the integration of STEM across the K-12 curriculum has incorporated a variety of approaches and outcomes rather than a 'single, well-defined experience' (Honey, Pearson, & Schweingruber, 2014, p. 2). Recent reports (e.g. *Next Generation Science Standards* [NGSS], *Core State Standards for Mathematics* [CCSSM]; and *the* STEM Task force Report, 2014) call for deeper connections among the STEM subjects to mirror real-world practices where STEM disciplines do not exist in isolation. For example, the STEM Task force Report (2014) in the United States highlighted the importance of 'cohesive and active teaching and learning approaches' that encompass 'real-world problem-based learning' for meaningful integration to be achieved (p. 9). However, providing similar experiences in the classroom is challenging since equitable representation of the four disciplines through STEM-integrated approaches is difficult to achieve (e.g. English, 2016). Generally, one STEM discipline has a dominant role and the inclusion of concepts from other subjects supports or deepens learning in the targeted discipline (Honey et al., 2014). Furthermore, connecting concepts across disciplines is challenging for students who are familiar with learning content in discrete subject areas (Honey et al., 2014). As such, research is required to find successful approaches that connect the four disciplines in ways that improve student outcomes (Diaz & King, 2007; Honey et al., 2014). One way to do this is through engineering experiences housed in real-world contexts that contextualise mathematics, science and technology concepts.

Engineering design requires engineers to thread the STEM concepts through the designing and building process such that 'conceptual cohesion' is reached (Walkington, Nathan, Wolfgram, Alibali, & Srisurichan, 2011, p. 1). Modelling this through engineering design in education has become of interest more recently to the international community as a way of connecting STEM disciplines (Lucas, Claxton, & Hanson, 2014; Next Generation Science Standards [NGSS], 2014). For example, in the United States the NGSS represent a commitment to 'raising engineering design to the same level as scientific inquiry' (p. 103) so that students are better prepared for 'the major societal and environmental challenges they will face' (p. 103). Engineering design and scientific inquiry have commonalities since they both require investigation into a problem or question, although they differ in the process required for carrying out the investigation. Science inquiry generally begins with an investigable question where students choose the relevant experimental approach, design and carry out experiments in a replicable way, record results, analyse data and draw conclusions based on the evidence (Kolodner et al., 2003). In comparison, the goal of engineering design is to produce a workable model with no one correct method or procedure although generally there is an iterative design, test and re-design process. As such, engineering design may or may not include a focus on understanding scientific principles. Both approaches require students to collaborate, ask questions, carry out investigations, make observations and measurements and apply what they have learned (Kolodner et al., 2003); however, only recently have iterative engineering design processes been used as a context for scientific inquiry (Purzer, Goldstein, Adams, Xie, & Nourian, 2015; Wendall et al., 2014). In this study, we use engineering design as a context for developing science, mathematics and technology concepts.

In the new mandated *Australian Curriculum: Design and Technologies* syllabus (ACARA, 2015) where 'engineering principles and systems' is one of the 'technologies context,' students are required to explain science concepts applied to a system and 'consider how material properties and construction processes influence the design and construction of structures' (Australian Curriculum, Assessment and Reporting Authority [ACARA], 2015, p. 32). In this interpretation, there is considerable overlap between Design and Technology and engineering design. However, engineering design also incorporates iterative stages; that is, designing a product, testing it and redesigning it based on previous testing (English & King, 2015; National Research Council, 2014). Furthermore, researchers have defined characteristics that constitute 'engineering thinking' as a way to approach problems that include: systems-thinking, adapting, problem-finding, creative problem-solving, visualising and improving (Lucas et al., 2014). Lucas and Hanson (2014) suggest that teaching and learning approaches need to adopt these 'Habits of Mind' in the early years to develop the distinctive ways that engineers think and act for possible future engineering careers. Therefore, engineering design is more than just designing a technological solution. Rather it requires the use of an iterative design process requiring 'engineering thinking' to solve a problem underpinned by engineering principles (such as a scientific law or theory).

Not only do students require skills that afford connections across disciplines, but they also need prior knowledge and the skills to apply this to the design process. Preparing students to be competent in applying and integrating knowledge from a range of sources to solve an engineering design problem is at the core of a successful approach to STEM integration. However, the challenge is to design tasks (or problems) that enable students to apply deep conceptual understanding of core science and mathematics concepts that are not overshadowed by the construction challenge. Research has shown that this has been a problem with engineering tasks where the science concepts are overlooked when the motivation to produce an artefact takes precedence (Roth, Tobin, & Ritchie, 2001). Well-designed activities that enable students to demonstrate STEM connections are needed.

We were interested in researching how fifth-grade children applied science, mathematics and technology concepts when given an optical engineering problem to solve using an iterative Engineering Design Model (see Appendix 1). These children were approximately 10–11 years old which situates them in the age bracket where interest in STEM is emerging. As such, we adopted the engineering design model from *pbs.org model* and used it to structure the activity. While such a unit is naturally underpinned by the science concepts of light, we designed the unit to enable the application of concepts from all three disciplines, science, mathematics and technology.

Initially, two broad questions guided our study:

1. How do students apply knowledge across disciplines to design and build an optical instrument?
2. How does the iterative engineering process afford opportunities for students to advance their knowledge and application of STEM concepts?

Specifically, we were interested in the following three questions that focused our research.

(1) How are STEM concepts expressed through the process of drawing the design sketches?
(2) How are these STEM concepts used in the construction of the optical instrument?
(3) What changes did the students make to the optical model in the second design?

We first give consideration to our theoretical and conceptual framework.

Conceptual framework

Situated cognition and sociocultural approaches to engineering activities

Our engineering activities that contextualise STEM concepts in design-based engineering experiences reflect the theoretical perspectives of situated cognition and sociocultural approaches to teaching and learning, as well as drawing upon the design-based approaches to primary and middle school engineering activities where design prototypes are products of scientific, mathematical and technological inquiry (Wendell, Kendall, Porstmore, Wright, & Rogers, 2014).

The situated cognition perspective suggests that a student's cognition is embedded within, and cannot be separated from, the situation where they engage in meaningful activities in a community of practice (Lave & Wenger, 1991; Wendell et al., 2014). From this perspective, engineering design can be considered a sociocultural activity that situates the use of STEM concepts in a meaningful context (e.g. creating a useful optical instrument) (Brown, Collins, & Duguid, 1989; Lave & Wenger, 1991). Furthermore, sociocultural views of learning are premised on the idea that knowledge is socially constructed through the interactions that occur in the complex social world of the classroom. Originating in Vygotsky's (1978) work, this perspective suggests that the roots of our intellectual functioning appear in our surroundings and through interactions with others before they appear internally. Using this theoretical perspective, the learning that occurs in a primary classroom does not focus solely on a student's engagement with a specific activity but rather their relation to the social activity as they co-construct knowledge with peers and teachers. In particular, a sociocultural approach to STEM-integrated activities affords students opportunities to learn science, mathematics and technology facts, methods and processes related to the situated practices (e.g. designing an optical instrument). Through this approach, the interactions that occur in the classroom contribute to how they come to see STEM concepts and themselves as learners and knowers of STEM. Therefore, the collaborative work in which students engage is central for students to connect STEM concepts.

Learning STEM concepts through design-based approaches

Our research adopted a similar conceptual framework to previous studies (e.g. Kolodner et al., 2003; Penner, Lehrer, & Schauble, 1998; Roth, 1996; Wendell et al., 2014), where the design process led to the construction of a physical product. In all of these studies, the designing and building process was a mediator of students' application of STEM concepts. Each study contributed to understanding better how students developed STEM concepts during design-based approaches.

In Wendell et al.'s (2014) work, overarching engineering design problems that required the use of Lego as contexts for exploring science concepts showed students developed deep reasoning about how things work. Furthermore, Wendell and Lee (2010) found that using workbooks for students' drawings and reflections facilitated elementary students' learning of science through engineering design activities. Penner et al., (1998) afforded children opportunities to design models of the human elbow where children used graphs and data tables to construct connections between the concept of force and the location of the attachment point of the biceps. In such a way, students used mathematics to analyse data that led to science understandings about their model that depicted the workings of the human elbow.

Kolodner et al. (2003) have worked extensively on developing a Learning By Design (LBD) project-based inquiry approach for engaging students in science learning through design and build challenges. For example, one unit titled 'Vehicles in Motion' enabled students to learn about forces and motion by designing and redesigning vehicles and their propulsion systems. Their work has shown how innovative design-based units can be successful for teaching science concepts if carefully constructed and implemented. Roth (1996) researched elementary children who were engaged in an engineering design environment where the emerging artefact became the tool for structuring the design process and afforded discursive and practical actions. Likewise, Roth's work was important for highlighting the situated learning of children as they designed engineering structures such as towers.

All of these studies (i.e. Wendall et al., 2014; Penner, et al., 1998; Roth, 1996; Kolodner et al., 2003) required students to keep written or pictorial records while solving the design problem as well as engage in the re-design process. Also, the drawing of sketches was important for analysing the progression of students' ideas over time and for representing science, mathematics and technology concepts that were emerging (see e.g. Wendall et al., 2014, p. 157). In a similar way, we adopted the drawing of sketches to show students' developing ideas through the design process and as evidence of the emerging mathematics, science and technology concepts.

Sketches/drawings as a tool for representing concepts and designs

Our study was influenced by previous research in science education that used drawings as a useful tool for determining students' level of conceptual understanding in the content areas of photosynthesis, evaporation, plants, the human body and animal internal structures (Köse, 2008; McNair & Stein, 2001; Prokop & Fancovicová, 2006; Prokop, Prokop, Tunnicliffe, & Diran, 2006; Schilling, McGuigan, & Qualter, 1993). Unlike our study, these studies focused solely on science concepts represented through drawings. In particular, Köse (2008) used five different levels to code students' conceptual understanding of photosynthesis varying from Level 1 – no drawing, to Level 5 – comprehensive representation of photosynthesis and respiration. However, there has not been any research using drawings for analysing students' conceptual understanding of optics.

Furthermore, we were influenced by Song and Agogino's (2004) research on students' designer sketching activities in product design teams. They used metrics to categorise students' sketches including representation (2D and 3D), annotation (type of support notation including labels, lists narratives, dimensions and calculations) and five levels of detail varying from Level 1(i.e. a line drawing with no details or annotations) to Level 5 (i.e. 2D drawings that show the entire product form). Song and Agogino (2004) found correlations between sketching activities, the variety of the concept sketches (i.e. sketches that displayed technological concepts) and design outcomes. As such, their study highlighted the importance of design sketching for the quality of the designed solution as well as the collaborative experience of the design process (Song & Agogino, 2004). We elaborate on our coding categories that were influenced by the work of Köse, (2008) and Song and Agogino (2004) in the methods section.

Engineering design activities

Science education research in the past has focused on science concepts that underpin the designing, making and building of an artefact where these activities are housed in either engineering or technology contexts (e.g. Fleer, 1999; Roth, 1995; Roth et al., 2001). The research has found that the application of science is 'exceedingly complex' (Gardner, 1992, p. 140) and as students design and build an artefact, careful teacher scaffolding is needed to draw out the science principles (Roth et al., 2001). However, three positive outcomes have been found when children engage in design-based engineering activities where there is a problem to solve; first, children can develop complex ways of talking about science and engineering issues that are personally relevant to them (Roth, 1996); second, students demonstrate a 'flexible' approach through the design process by framing and re-framing problems and solutions (Roth, 1996, 1995, p. 371); and third, children are capable of generating sophisticated design briefs and questions (Fleer, 1999). In secondary classrooms research has found that engineering design activities provide a rich context for understanding the value of scientific reasoning (Silk, Schunn, & Strand-Cary, 2009); and are effective for teaching difficult core chemistry concepts (Apedoe, Reynolds, Ellefson, & Schunn, 2008).

More recent research highlights the importance of integrating engineering practices in primary science classrooms to foster student interest, participation and self-concept in engineering and science (Capobianco, Yu, & French, 2015). Capobianco et al. (2015) developed engineering activities based on the Boston Museum of Science's Engineering is Elementary curriculum (http://www.eie.org) that included building Lego models (e.g. creating a pair of Lego dancing birds that can rotate and sing) and focused on teaching science concepts through the design process. Of relevance to the present study is their finding that engineering activities in the elementary school provided an authentic context for students to learn how engineers solve problems, work in teams, and use science and mathematics. Another study by Marulcu and Barnett (2013) found that fifth-grade students significantly improved their understanding of simple machines from an engineering design-based and Lego-oriented unit, suggesting that engineering education in elementary schools is suitable as a context for teaching science. In a similar way, this study situates the learning in an authentic engineering context (i.e. where the product has a real-world use) and requires students to work in teams, and apply the science, mathematics and technology concepts to their designs. Despite promising outcomes, there has been little research on how best to design engineering activities that integrate not only science but all STEM disciplines and whether such activities afford students opportunities to demonstrate sophisticated ideas across the disciplines. The sociocultural and situated practice theoretical lens as well as the conceptual framework described above underpinned our study by providing a lens through which we could view the data.

Methods

In this section we describe the participants, the engineering activity, the data sources and analysis. The participants, focus groups, number of students, data samples used and analytical techniques are summarised in Table 1. Following this, we provide an extensive explanation of the participants, activity, data sources and analysis.

Participants

This study was part of a three-year longitudinal study that focused on the primary grades (i.e. grades 4–6) and built on previous research (e.g. English et al., 2013). We worked with the different grade levels in each year of the study developing engineering units, implementing the units with teachers and researching student outcomes (e.g. Grade 4 – 'designing and flying planes' (Aerospace Engineering); 'tumbling towers' (Civil Engineering); Grade 6 – 'medivac mission' (Materials Engineering)). This study focuses on the fourth activity, which required students to design an optical instrument. Students from three Queensland (Australia) private and state schools participated in the three-year study representing the two main education sectors. For this study, data were collected in the second year from four private school classes from two of the schools (St Anne's and City School – pseudonyms). The students were in the fifth grade (mean age = 10 years 8 months). Both schools were private girls' schools in a metropolitan city attracting families from middle to upper socioeconomic status. These two schools were chosen for data collection and analysis for two reasons: first, the timetable afforded students opportunities to complete the activities fully; and second, most students were fluent in the English language. In each class there were two focus groups of three students based on the teacher's recommendations of mixed achievement levels whom they selected on ability to discuss problems and work together (a total of eight focus groups; $N = 24$ students). The teacher assured us that the groups were representative of the majority of students in the class. There were only two focus groups in each class because of time and resource limitations since we wanted to transcribe verbatim the conversations and scrutinise the video data to complete fine-grained analysis of in-class interactions. All focus groups were video and audio recorded during the engineering activity. The parents or guardians of all students in the study signed ethical permission forms that allowed video and audio recordings and the collection of data relevant to the study. The University and Education Departments through which the study was conducted granted ethics approval.

Table 1. Summary of data and analysis.

School	No. of classes	No. of focus groups in each class	Total no. of focus groups in school	No. of students in each focus group	Total no. of students	Data samples used	Analytical techniques
St Anne's	2	2	4	3	12	Audio and video recordings	All recordings fully transcribed. Ethnographic analysis of patterns seen and heard in conversations as well as coding for evidence of science, technology and mathematics concepts. Coding was used initially to divide the text into segments, examine the codes for overlap and redundancy and combine the codes into themes (Creswell, 2002). Similar codes were aggregated together to form the broad themes initially that were refined through the iterative process of revisiting the coding for fine-tuning. Patterns of coherence and contradiction emerged (Tobin, 2006)
						Workbooks	Design sketches: Analysed for 'recurrent instances' of mathematics, science and technology concepts present on the design sketches (Wilkinson, 2011, p. 170). Instances were identified across the data set and grouped together by our coding system. Two to three iterations of coding were conducted to reach consensus. Basic statistical data were calculated. Final coding system is in Tables 2 and 3 Written Answers: Entered into a spreadsheet and coded for core science, mathematics and technology concepts. Iterative refinement of codes occurred
						Field notes and in-class observations	Provided a starting point for analysis through identifying how and when students applied STEM concepts. Provided triangulation of themes that emerged

City School	2	2	4	3	12	Audio and video recordings	All recordings fully transcribed. Ethnographic analysis of patterns seen and heard in conversations as well as coding for evidence of science, technology and mathematics concepts. Coding was used initially to divide the text into segments, examine the codes for overlap and redundancy and combine the codes into themes (Creswell, 2002). Similar codes were aggregated together to form the broad themes initially that were refined through the iterative process of revisiting the coding for fine-tuning. Patterns of coherence and contradiction emerged (Tobin, 2006).
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						Field notes and in-class observations	Provided a starting point for analysis through identifying how and when students applied STEM concepts. Provided triangulation of themes that emerged
Totals		No. of focus groups: 8		No. of students:24			

Table 2. Coding scheme for design sketches.

A.	The parts of the optical instrument were not annotated but nevertheless could be discerned clearly from the sketch. A mirror and/or lens was/were drawn. Angle of the mirror was not measured accurately. No measurements were labelled on the design sketch
B.	The parts of the optical instrument were annotated (e.g. tubes, eye or eye piece, lens – concave/convex, light ray). A mirror and/or lens were clearly visible. The mirror's angle approximated 45^{o} (as in a periscope) and/or the lens was in an appropriate position for magnifying or reducing the size of the object
C.	Light rays were drawn from the object to the eye or eye piece; however, the light rays were represented with some inaccuracies; that is, not perpendicular to the eye or not straight, or not reflected off the mirror where angle of incidence does not equal angle of reflection
D.	Three-dimensional perspective was featured through the drawing of parts of the optical instrument. Measurements showing length, width, height of instrument were included and/or number of each resource (e.g. tubes) required
E.	Light rays were drawn reflecting off one or two mirror/s or through lens/es with some accuracy; that is, approximately the angle of incidence equals the angle of reflection as identified through the drawing. Arrows might have been marked on the rays and the mirror angle might have been marked. Mirror angle approximated 45^{o} for a periscope model
F.	Light rays were drawn reflecting off one or two mirror/s or through lens/es with accuracy; that is, the angle of incidence equals the angle of reflection as identified through the drawing and the angle of the mirror is marked at 45^{o} and/or arrows were on the ray diagram
G.	Accurate representation of the use of multiple mirrors showing reflection of light off mirrors from light source to eye was displayed

Table 3. Design levels.

Level 0	neither (A) nor (B) was evident
Level 1	(A) and/or (B) were evident only
Level 2	(A) and/or (B) and (C) only were evident
Level 3	(A) and/or (B) and (E) with (D) possible
Level 4	(A) and/or (B) and (F) with (D) possible
Level 5	(A) and/or (B) and (G) with (E) or (F) and (D)

The engineering activity

We created a novel Optical Engineering activity that required students to design and build an optical instrument that could 'spy' on a person or view a hidden object. The activity was set in an engineering context where students were introduced to the work of Optical Engineers (e.g. designing high-speed cables or lasers for cutting-edge surgery and defense). Students were instructed to develop a design prototype for an optical instrument that could be marketed for public use. Students had access to resources such as cardboard tubes, lenses, mirrors and tape. For many of the activities, engineers visited the classes providing valuable insights to enhance the activity; however, the engineers were advised not to direct the students on how to undertake the activity.

The authors designed the activity in consultation with all of the teachers, with whom they met on two occasions to plan the activities that complemented their prepared units of work and built on students' existing mathematics, science and technology curricula as well as the fifth-grade mandated syllabus learning outcomes. The core mathematics concepts included choosing appropriate units for measurement and measuring angles with a protractor (ACARA, 2015). The technology core concepts included creating a system through which light could travel, choosing appropriate materials, and the impact of construction on the design (ACARA, 2015). Also, technological processes were encouraged such as generating, developing and communicating design ideas when making design solutions (ACARA, 2015).

The activity was designed in two parts. Part A consisted of the *Primary Connections* module on Light (Australian Academy of Science, 2012) where students completed the preliminary activities that developed the following core science concepts relevant to this task: light travels in straight lines; light can be absorbed, reflected and refracted; and the angle of incidence equals the angle of reflection. Students also were taught how to use ray diagrams to represent light rays and how to measure with a protractor. Part B consisted of workbook activities that introduced students to the work of optical engineers, explored the uses of lenses, introduced convex and concave lenses through hands-on activities, highlighted the development of microscopes and telescopes, and culminated with the design activity reported in this study. For example, one activity required students to measure and record focal lengths for various lenses. Another activity required students to use animations to explore the refraction of light through lenses using ray diagrams (e.g. http://www.bootslearningstore.com/ks2/eyesight.html).

Teachers in all four classes implemented the activity by following the workbook structure. For the culminating activity, which is the focus for this paper, groups were given one of four scenarios to solve (see Appendix 2 for a summary). Both authors were present when students completed the final three-hour section; that is, designing, building and redesigning an optical instrument. Our role in the final three-hour section was to observe students carefully, especially the focus group students, to gain a unique picture of the learning that was occurring during the engineering component of the task. During this time we wrote field notes. Most students had completed three prior engineering units where design sketches were a component.

Data sources and analysis

We adopted a collective case study approach where several cases were studied to form a collective understanding of the research questions (Stake, 1995). To gain a richer understanding of the use of design sketches during the iterative process, we included eight focus groups for workbook analysis complimented by ethnographic analysis. Ethnographic analysis affords opportunities to interpret patterns seen and heard in the student–student conversations in the classroom setting (Creswell, 2002). As such, the analysis gave a unique picture of the learning that was occurring during the group conversations. Our presence in the classroom during the activities enabled us to make observations about how students applied STEM concepts while building the optical instrument that provided a starting point for the analysis. Through ethnographic analysis, coding was used initially to divide the text into segments, examine the codes for overlap and redundancy and combine the codes into themes (Creswell, 2002). Similar codes were aggregated together to form the broad themes initially that were refined through the iterative process of revisiting the coding for fine-tuning. The themes represent patterns of coherence and contradictions (Tobin, 2006). Contradictions that do not support or confirm the themes provide important insights into the complexity of the interactions (e.g. students were unable to apply the science concepts pertaining to light rays when discussing the positioning of lenses in the optical instrument). Combining workbook and design sketch analysis with ethnographic analysis was a strength of this study since we could triangulate the data across the data corpus finding interconnections that were new and interesting (e.g. student conversations while drawing design sketches highlighted the importance of the design sketch for applying science and mathematics concepts). In sum, the data included students' workbooks, video and audio recordings of focus groups, in-class observations and field notes.

First, we conducted content analysis (i.e. analysing for core science, mathematics and technology concepts) on the workbook responses from the groups focusing on their first and second design sketches by coding for mathematics and science concepts. In the workbook analysis we focused primarily on mathematics and science concepts; however, technology concepts became more apparent when students were building their instruments.

Influenced by the research of Köse (2008) and Song and Agogino (2004), we designed our own categories for coding students' design sketches for the optical instrument including some of the metrics by Song and Agogino (2004) as well as conceptual understanding relevant to optics at a Grade 5 level. Based on the mandated science syllabus (ACARA, 2015), we determined the following science concepts as important for designing an optical instrument that could be represented on drawings through ray diagrams or annotations: light travels in straight lines; light can be absorbed, reflected and refracted; and the angle of incidence equals the angle of reflection. In a similar way, we determined the core mathematics concepts that could be represented on drawings to be: choosing appropriate units of measurement and measuring angles with a protractor (ACARA, 2015). The core technology concepts that could be represented through drawings and the final model included: creating a system through which light could travel, choosing appropriate materials and the impact of construction on design (ACARA, 2015).

We analysed the data for 'recurrent instances' or aspects of the mathematics and science concepts that were present in many of the design sketches. (e.g. the representation of ray diagrams on the sketches) (Wilkinson, 2011, p. 170). These instances were systematically identified across the data set and grouped together by our coding system. This coding provided basic statistical data such as the percentages of students who represented core science and mathematics concepts on their sketches at various levels of sophistication. The final coding system is explained in the next section.

Design sketches

We analysed 24 workbooks from the eight focus groups coding for the features we identified as salient for representing core mathematics and science concepts at varying levels of sophistication and accuracy. In identifying these features we considered students' application of science concepts related to the reflection of light (e.g. ray diagrams) and lenses (e.g. light rays passing through the lens and converging or diverging to a point), as well as mathematical concepts that included dimensions of the instrument and the measurement of angles including protractor use. Furthermore, we considered students' use of annotation and perspective applied in one of the earlier activities (see e.g. English & King, 2015). This was developed from Song and Agogino's (2004) work where the annotations such as labels and dimensions supported the explanation of aspects of the model. The final coding scheme of features displayed in the students' first and second design sketch is in Table 2. The coding of students' design sketches revealed six levels of increasing sophistication and accuracy in the representation of science concepts pertaining to light as well as mathematical concepts related to angles and measurement (Table 3). The authors categorised the students' workbook responses, including their initial design sketches and redesigns and repeatedly checked to ensure consistency was achieved. If there was disagreement, we checked our coding with the research assistant to reach a consensus. Often we engaged in two to three iterations of coding by refining the descriptions repeatedly until we were confident that the final codes and descriptions were accurate. We reached 100% agreement with the final coding of the design sketches.

A brief summary of the analysis of each level is explained below with a representative example for each level.

Level 0: This level did not consist of A or B (see Appendix 2); that is, the student did not do a design and left the page blank. This only occurred on one occasion for the design and redesign sketches out of a total of 24 students ($N = 24$; 4.2% of students).

Level 1: This first level consisted of basic design sketches where students drew an optical instrument that contained a mirror and/or a lens. Importantly, there were no light rays drawn at this level and angles were not marked clearly or measured using a protractor. No measurements were labelled on the design; however, there could have been some labels of parts of the instrument. Across the focus groups from the five classes, ($N = 24$) there were 16.7% of initial designs at this level. At the redesign level there was a slight increase at 20.8% (e.g. see Figure 1).

Level 2: At level two, there were a number of sub-components that emerged in which the designs displayed Level A and/or B as well as the presence of light rays. However, the ray diagrams lacked accuracy with the measurement of angles; for example, angle of incidence did not equal angle of reflection. For this level, there were 16.7% of design sketches coded at Level 2 for the first design sketch and slightly less, 12.5% in the second design sketch (e.g. see Figure 2).

Level 3: At level three, the design sketches displayed Level A and/or B as well as the representation of the light rays with some accuracy. There were 20.8% of first designs coded at this level and 25% in the redesign. Perspective might have been included at this level (e.g. see Figure 3).

Level 4: At level four, the design sketches accurately showed the angle of incidence equals the angle of reflection and the angle of the mirror was marked. There may or may not have been arrows on the ray diagrams. Perspective might have been included. There were 37.5% at this level for the first design and 37.5% in the second design (e.g. see Figure 4).

Level 5: At this highest level, students used multiple mirrors to show the reflection of light accurately with perspective and measurements included (e.g. see Figure 5). Design sketches at this level only occurred twice in the first design 8.3% and there were none in the second design.

Following this analysis, we constructed a spreadsheet coding students' answers to 20 questions in the workbook that students completed through the design, construct and redesign stage of the activity. Content analysis was used on these answers to code for core science and mathematics concepts (i.e. light travels in straight lines; light can be absorbed, reflected and refracted; the angle of incidence equals the angle of reflection; choice of appropriate units of measurement, angle measurements using degrees, reference to a system through which light could travel, appropriate materials and explanation of the impact of construction on design (ACARA, 2015)). Finally, we analysed video and audio data of focus groups. Each focus group's conversations were transcribed verbatim (a total of approximately 5 h and 17 min).

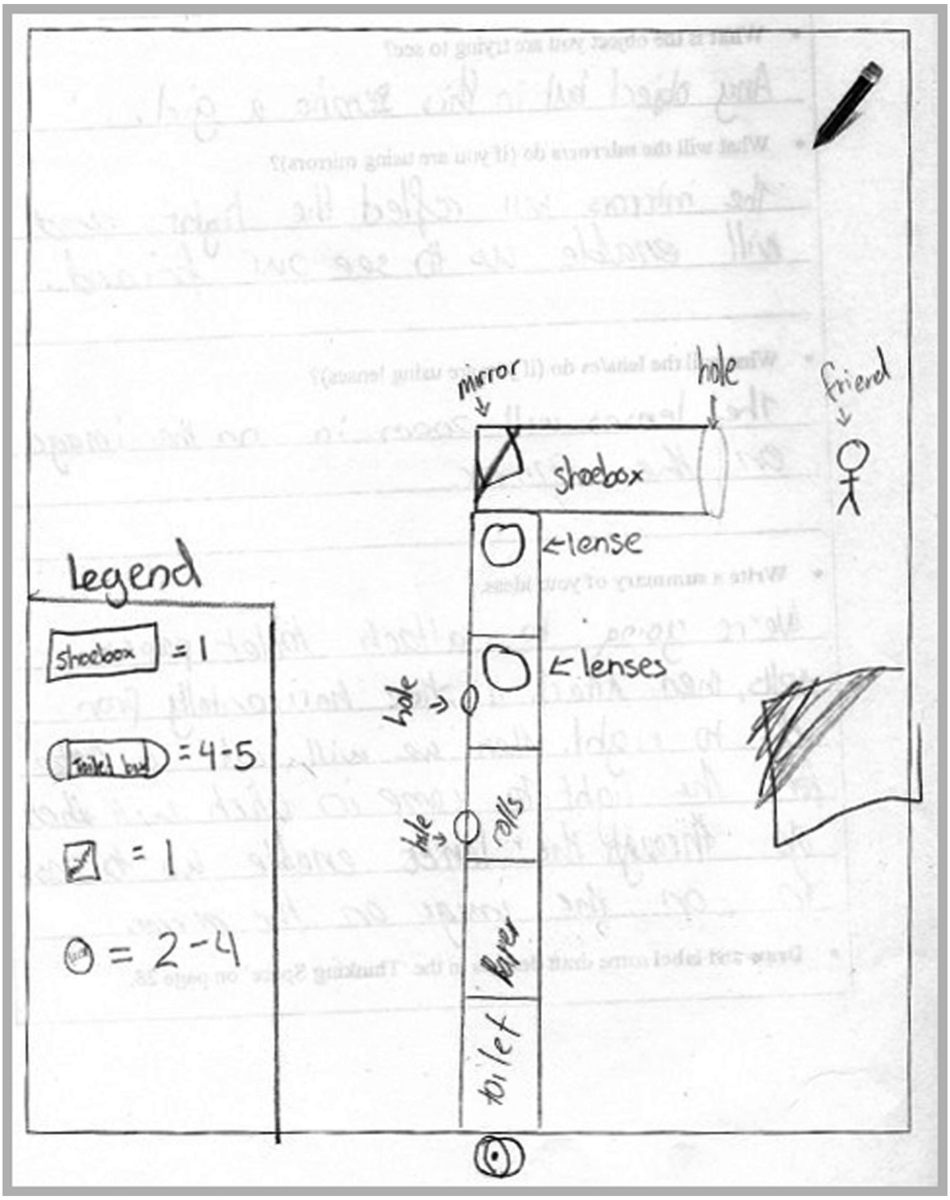

Figure 1. Sample of level 1 design.

Our ethnographic analysis focused on two focus groups within one class (A) from City School. That is, we aimed 'to provide contextual, interpretive accounts' of the students' interactions where the application of the STEM concepts was occurring (Wilkinson, 2011, p. 174). Focus Group 1 was chosen because their first design was complex (i.e. more than a periscope model that many groups had drawn) and in their conversations they negotiated their design choices providing insights into advanced conceptual ideas underpinning their design. We decided that this group would provide insights into creative applications of STEM concepts that were achievable through collaborative

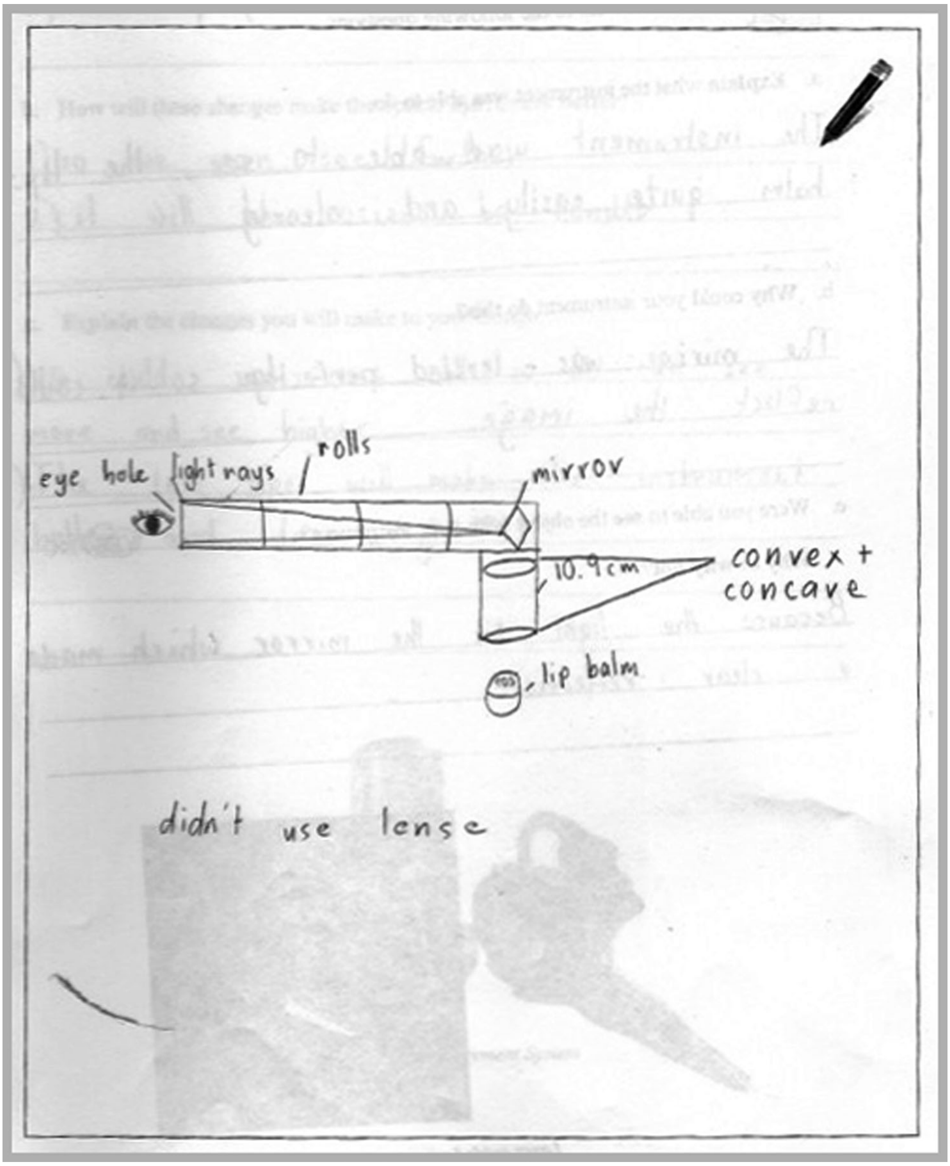

Figure 2. Sample of level 2 design.

engagement. Focus Group Two students designed a more 'typical' periscope model representative of the majority of groups in the class. We decided that they would provide insights into the learning that was characteristic of most students. Focus Group 1 students (i.e. Charmaine, Cathy, Connie – pseudonyms) were given scenario five (design an optical instrument to spy on a teacher in the staffroom) and focus Group 2 students (i.e. Sarah, Terese, Polly – pseudonyms) were given scenario four (design an optical instrument to see a tennis ball in a gutter of the school building).

To understand further how students applied these concepts during the process of designing and building an optical instrument, we reviewed the transcripts of the focus

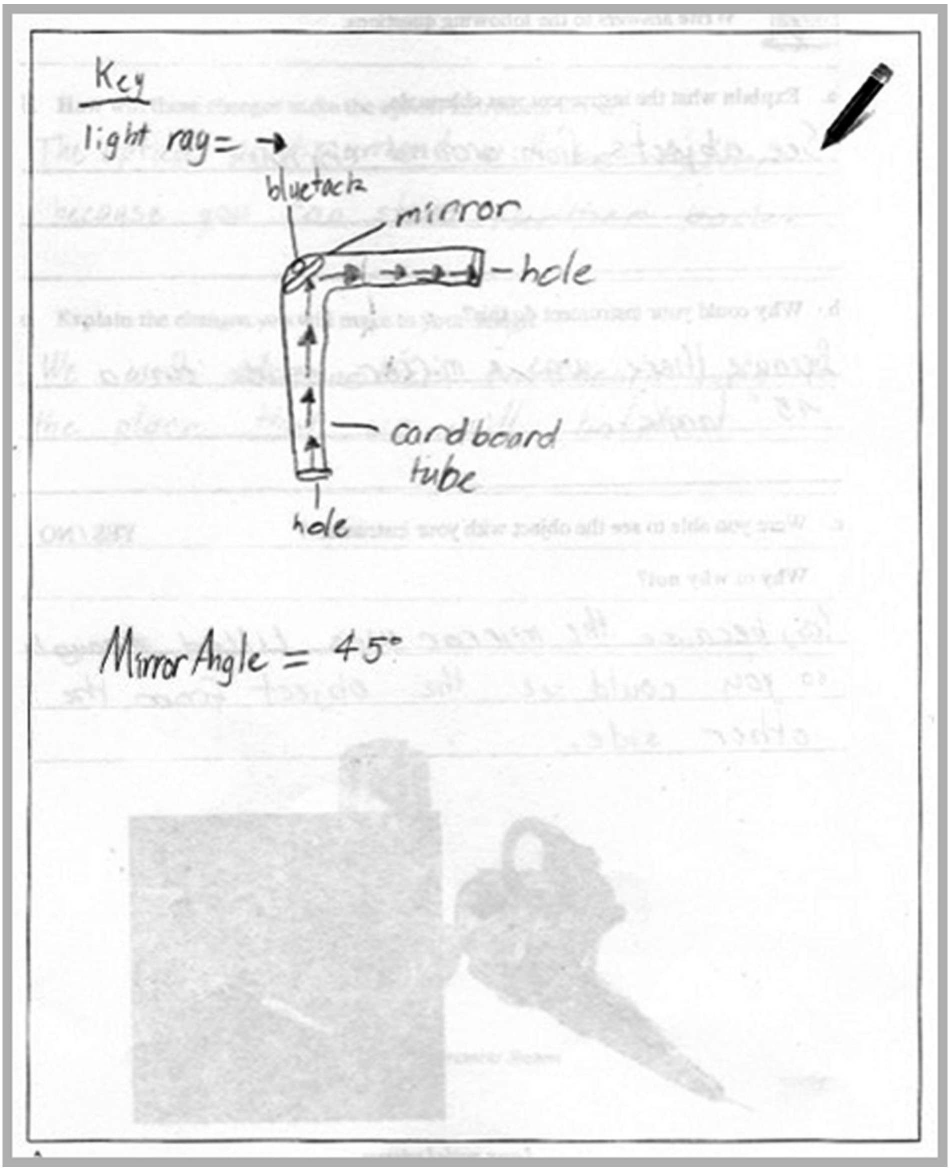

Figure 3. Sample of level 3 design.

group students' work for the entire activity coding for evidence of science, technology and mathematics concepts. We became aware that the interactions between the students in the groups contributed to the design process as they applied science, mathematics and technology concepts. We returned to salient sections of the videos and conducted iterative refinement cycles of analysis to draw out key findings (Lesh & Lehrer, 2000). This provided triangulation of data as well as fine-grained evidence of the importance of the social construction of knowledge during the design sketch stage. We present the three key findings in the results section showing the importance of the design sketch stage for application of STEM concepts, the use of experimentation in the construction stage for a simpler

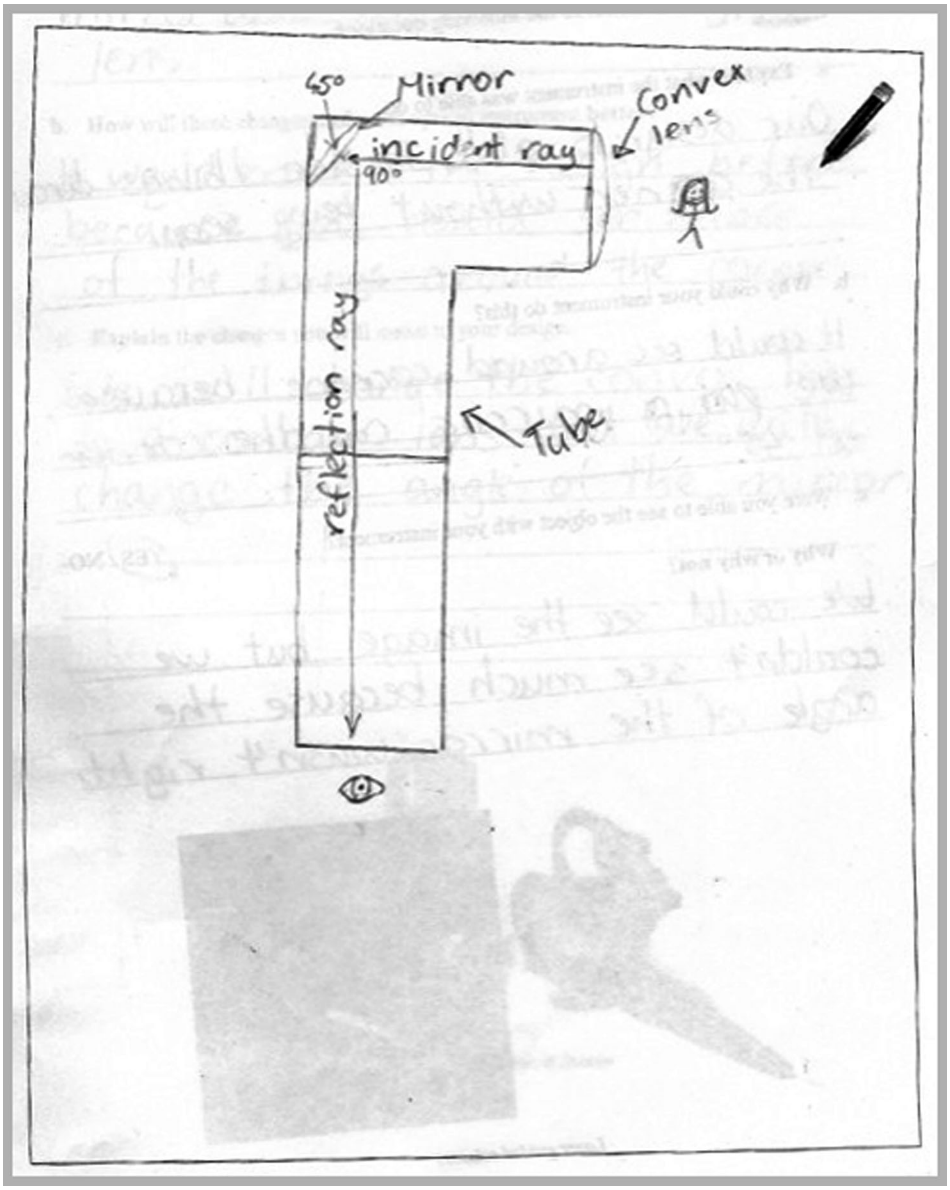

Figure 4. Sample of level 4 design.

'working' model and the importance of the redesign stage for refining the model. Overall, we show how the application of STEM concepts can occur in a well-designed task when students have appropriate prior knowledge. We refer to students' sketches of their designs as 'design sketches' to distinguish from other aspects of the design process.

Results

Research Question 1: How are STEM concepts expressed through the process of drawing the design sketches?

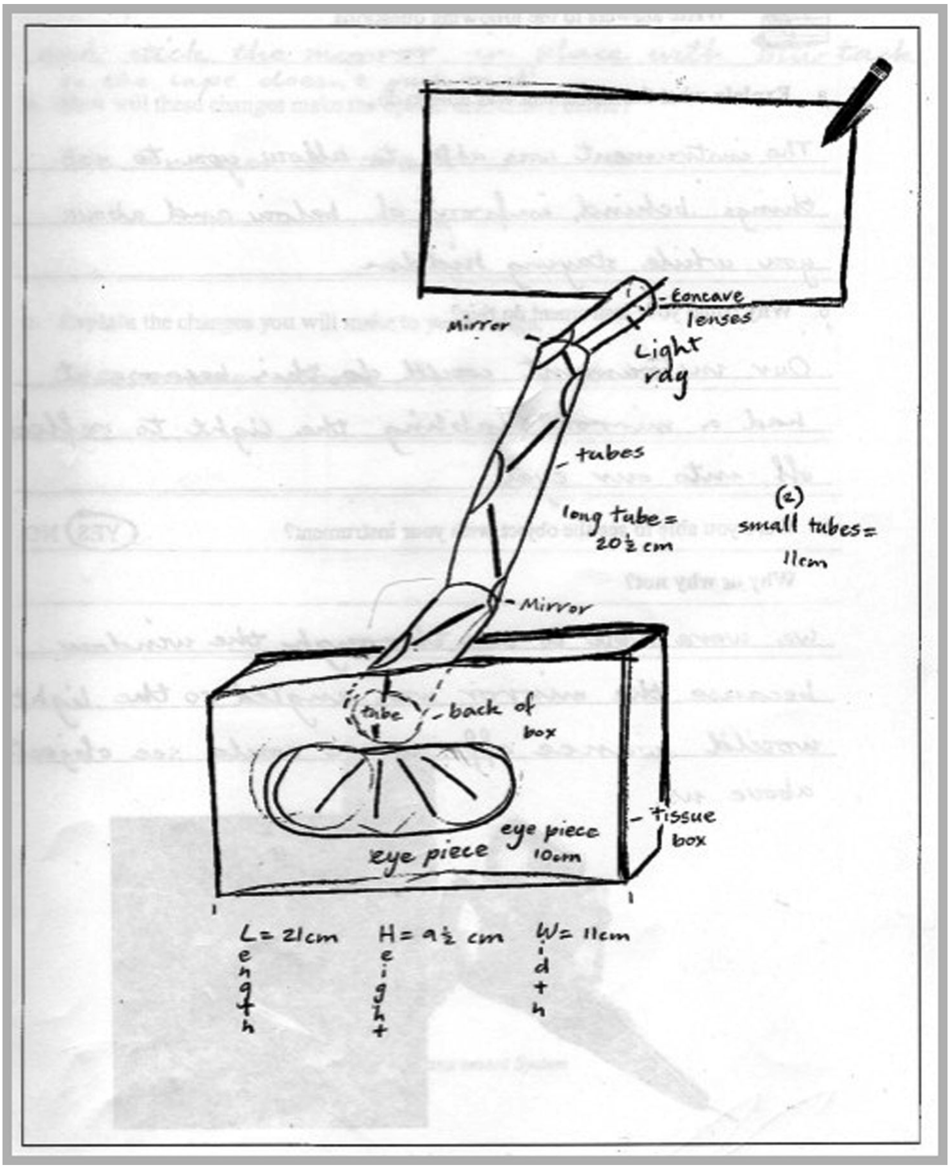

Figure 5. Sample of level 5 design.

The analysis revealed that 83.3% of students represented accurate scientific understandings about the reflection of light off mirrors through ray diagrams on their design sketches for the first design and 79.2% for the second design. Interestingly, when a lens was included in the design sketch, ray diagrams representing the path of light through the lens did not show the rays converging or diverging perhaps indicating that the physics concepts of lenses was too difficult for students at this primary school level. Hence, lenses were only coded for their identification as convex or concave (see Level A and B Table 2). Through their first design sketches, students demonstrated that light would come from an illuminated object (e.g. teachers in the staff room) travel in straight lines through the instrument and reflect off one/two or multiple mirrors to the eye where the angle of incidence equals the angle of reflection. The majority of design sketches showed the mirror at a 45^{o} angle for an instrument that was modelled on a periscope (excluding Group 1 who used multiple mirrors). Also, on further analysis of the mathematical concepts, 45.8% (11) of first designs included dimensions labelled on or near the optical instrument, angles measured accurately and/or the correct number of each resource noted. In such a way, the application of science (light travels in straight lines, angle of incidence equals angle of reflection) and mathematics concepts (measuring angles) was present in these sketches. Interestingly, there was not much change in the level of sophistication or application of science and mathematics concepts in the second design, which is explored further in Research Question 3.

In sum, the coding analysis showed evidence of a combination of mathematics and science principles in students' design sketches at Level 3 or above. That is, approximately two-thirds of students (66.6%) demonstrated application of relevant science and mathematics principles at Level 3 or above for the first design and slightly less for the second design (62.5%). Students demonstrated light reflected off mirrors, travelled in straight lines and they could measure accurately the angle of incidence, which equalled the angle of reflection. Furthermore, most sketches at Level 3 and above showed perspective with suitable dimensions.

Student–Student interactions

We were encouraged by these data that showed a large percentage of students expressed science and mathematics concepts on their first and second design sketches. Also, the design sketches showed evidence of students representing the instrument as a 'system.' We wanted to understand better how mathematics, science and technology concepts were integrated through this collaborative engineering design process, so we searched for evidence through analysing the transcripts of the two focus groups. Interestingly, we found that the collaborative nature of the group work influenced students' designs as they shared ideas between group members. Furthermore, we found that the conversations predominantly focused on science concepts as applied to the technological aspects of creating a system; that is, positioning the resources so that the reflection of light off the object will pass through the instrument to the viewer and less frequently on the mathematics concepts. We coded students' conversations by highlighting where their discussions represented the core science/technology concepts from the ACARA syllabus.

One representative example occurred when students in Group 1 (i.e. Cathy, Connie, Charmaine) had accessed the resources detailed in their design sketch in Figure 5 (i.e. a tissue box, tubes and a large mirror) to help create their sketch. Prior to the following vignette, the group had decided to use five small mirrors positioned through three tubes (see Figure 5) with a big mirror at the back of the tissue box to reflect the image to their eyes. In this excerpt, they were drawing the design sketch and stopping to look at the resources and talk about where they would put them. They were deciding where to put the big mirror, which they had initially thought would go at the back of the tissue box opening to reflect the image that came through the tubes to the opening (see Figure 5). In the following student–student interactions, Cathy applied the science concept of reflection of light as she used the resources to explain her reasons for suggesting changes to the design sketch. Interestingly, Cathy's ideas suggest she was viewing the instrument as a whole 'system' that needed to work. The following excerpt shows a 58-second exchange where Cathy convinces Connie and Charmaine that they do not need the big mirror. The excerpt highlights the application of science concepts: that light travels in straight lines and reflects off surfaces. Also, the excerpt highlights the technological concepts of creating a system through which light could travel, choosing appropriate materials and the impact of construction on design. The following excerpt supports the outcomes by highlighting the importance of students' discussion about the science concepts applied to the resources in both design sketches and the 3D model for creating a system that works.

Excerpt 1 – Focus Group 1 negotiating a change in design based on science understandings applied to a "system"

01	Cathy	Where's the mirror? Where's the big mirror?	*Science/Technology Concepts*
02	Charmaine	It's at the back. We need it at the back.	
03	Cathy	We don't need a big mirror at the back	*Choosing appropriate materials*
04	Charmaine	Yeah we do.	
05	Cathy	Why? It's gonna rebound off you do realise?	*Light travels in straight lines and reflects off surfaces*
06	Connie	Yeah it is	
07	Cathy	How? The tube's coming out of the back. It can't rebound off the back.	*Light reflects off surfaces*
08	Cathy	Why do we need a mirror there? *(referring to the big mirror in Charmaine's drawing)*	*Impact of construction on design*
09	Connie	*(Holds up A4 mirror sheet.)* So the picture bounces off there *(points to mirror sheet)* and comes here *(moves hand back over her shoulder representing reflection of light rays off mirror).*	*Light travels in straight lines and reflects off surfaces*
10	Cathy	But the tube – where's the tissue box. The tube is here. *(Places a small tube in the middle of a long side of the tissue box)* It comes – the tissue box – it comes through there *(the tube)* and into our eyes (*pointing to the hole in the tissue box which is the opening for viewing*). Oh actually it's here *(flips tissue box on its side and places tube on the bottom of the box, opposite to the hole where the tissues are pulled out.)* It comes into our eyes like that. *(showing that the rays come through the tube into the tissue box to the opening where the eyes are and there is no need for a big mirror in the tissue box for reflecting light)*	*Light travels in straight lines and reflects off surfaces* *Creating a system through which light can travel; Choosing appropriate materials; Impact of construction on design*
11	Connie	We don't need the big mirror	*Impact of construction on design*
12	Charmaine	I like the big mirror	
13	Cathy	Because it just comes through *(indicating that the light rays will just come straight through the tissue box and there is no need for a mirror to reflect light rays)*	*Creating a system through which light can travel; Light travels in straight lines*

The above vignette showed Group 1 students negotiating the design as they were drawing it. Cathy explained how the light reflected from the image will pass through the tube into the tissue box and reach the viewer's eyes (turn 10). Through modelling where the light rays will travel with hand gestures and use of resources, she convinced Connie that they did not need the big mirror at the back of the tissue box (turn 11). Cathy's sound understanding of light 'bouncing' from mirrors to reach the eye through a system was evident in this exchange. Furthermore, their design sketch was coded at the highest level of sophistication showing that previously taught science concepts on light and its reflective properties appeared in both the students' first sketches and in the conversations as they drew the first design sketch. The analysis shows the importance of a sound understanding of science, mathematics and technology concepts and access to resources for negotiating and expressing canonically accurate applications in the design sketch that can be applied to create a system.

Interestingly, we found a contradiction to students' accurate application of science concepts when they were referring to the lenses. The student–student conversations about the path of light through the lens in the first design sketch stage centred on students naming them as convex and concave lenses predominantly and referring to them as making the image bigger or smaller. In such a way, the students' discussion of lenses focused on the purpose of the lens rather than the path of light through each lens and how this will affect the image. We found that in their conversations, students were clarifying the role of concave and convex lenses with each other. While they were familiar with the function of a lens from previous work, there was confusion about which lens enlarged or diminished the size of the object and how they were to incorporate it into the design. Despite this confusion, Group 1 reached a consensus which was to include a concave lens at the top of the instrument (see Figure 5) and their reasons for this were recorded in their workbooks:

> The concave lens[es] will allow light to shine onto the mirrors. The mirrors will then reflect the remaining light among themselves until it reaches our eyes, allowing us to see the staff celebration clearly. (Charmaine – Focus Group 1)

A canonically accurate understanding of refraction of light through a lens was not present, highlighting a gap in students' prior knowledge. We return to the issue of lenses in the discussion.

The analysis showed that the collaborative drawing process afforded students opportunities to represent scientific concepts of light, mathematical concepts pertaining to geometry, angles and measurement, and technology concepts relating to how light travels through a system and choice of resources. Furthermore, the design sketch was important for students to negotiate their STEM ideas within the constraints of the problem using available resources in the allocated timeframe. In their first design, students chose resources that would make a system that enabled light to pass through the instrument, reflect off one or more mirrors and eventually reach the eye of the person looking through the device. Therefore, we argue that the integration of core science, mathematics and technology concepts was evident in this first drawing stage. Our findings contribute new insights into the importance of the collaborative drawing process for applying science, mathematics and technology concepts in STEM-based problems for primary children and the requisite prior knowledge for this important stage. These findings extend earlier work by Roth et al. (2001) who found that requiring students to represent ideas on design sketches led to scientific discourse. We have added to this by showing that the scientific discourse contributes to the connection of STEM concepts for a design solution. We then turned our attention to the construction and redesign stages.

Research Question 2: How are the STEM concepts applied to the construction of the optical instrument?

After the students completed the first drawing of their design sketch in their workbooks, the teacher told them they could begin to build their model. We analysed the transcripts and videos for evidence of how students built the instrument using the available resources. Fine-grained analysis of the focus groups showed that during the construction stage, students referred to the positioning of the mirror and lenses experimentally through trial and error in their group conversations. We present examples from both focus groups.

Focus group 1

Focus Group 1 used the design sketch initially to identify the resources required for the initial structure and positioning of the mirrors. However, as they began to build the model, they discussed the positioning of the mirrors and lenses through trial and error on six separate occasions for each as they positioned them to see through the instrument. Through our analysis, it was evident that the following STEM concepts were being addressed: creating a system through which light could travel, choosing appropriate materials, appreciating the impact of construction on design and applying the knowledge that light travels in straight lines. Despite a commitment to build the original design, the group soon realised that the design with multiple mirrors was too complex and a more realistic model was similar to a 'periscope.' In their discussions they referred to the periscope as being 'already invented' and that it was 'invented in World War One' recalling prior knowledge about the origin of the periscope and suggesting it was not the novel design they had drawn. However, they concurred that their model would be different because they were making it out of different materials since the original periscope 'would have had like metal' to make it. Another difference to the periscope model was that they included a lens at the point where the tube would meet the eye.

Through the student–student negotiations, the original creative ideas represented on the design sketches were narrowed to a working model that could be constructed within the timeframe using the available resources. We were surprised that such creative and complex design ideas were replaced with a less original working model but students were under time pressure to produce an instrument that worked. We return to this finding in the discussion.

Despite the differences between the design sketch and the model, students were pleased with their model explaining, 'you can see things upside down but it works' and expressed their satisfaction with the visibility through the instrument with comments such as 'that is so awesome.' The resulting optical instrument had one mirror rather than the five they had originally planned since the construction process, where they began to see how to make a working model, prevented them from creating the first design. Their final model resembled the design sketch in shape, structure and choice of resources (see Figure 6).

Focus Group 2

Focus Group 2 also used trial and error to position the tubes and mirror as indicated on their original design sketch; however, they struggled to include the lenses. One representative example of the trial and error approach occurred in this exchange when Terese

Figure 6. Group 1's first model.

was experimenting with two cardboard tubes and a mirror to see if she could align them so that she could see an image. The other group members joined in on the experimentation:

Excerpt 2 – Trial and error for construction of the optical instrument (Focus Group 2)

			Science/Mathematics/Technology concepts
01	Terese	We could stick the mirror	*Choosing appropriate materials*
02	Polly	Yeah. Yeah. That's why I tried to find the putty.	
03		*Terese has moved off camera. She is holding two cardboard tubes at a right angle, one roll pointing downwards. She has placed a small mirror in between the tubes. She is looking through the top tube. Students used a protractor to make sure it was a right angle.*	*Choosing appropriate materials; The impact of construction on design; Measuring angles*
04	Terese	I can see my tie	*Light travels in straight lines*
05	Polly	Oh really? Is it working. Let me see. Let me see. *(Terese holds*	*The impact of construction on design*
06		*tubes and mirror while Polly looks through the top tube.)* That is awesome.	
07	Sarah	Can I try?	
08	Polly	That's so cool. We're actually going to make something that works.	*The impact of construction on design*

In Excerpt 2, Terese holds two cardboard tubes together with an opening in the middle where she places a mirror and looks through the tube to see her tie (turn 04). The other group members look through the tube too and are encouraged by the outcome when Polly says 'that's so cool. We're actually going to make something that works' (turn 08). Interestingly, focus Group 2 had similar discussions about the placement of the mirrors on 12 other occasions, but only on two occasions did they experiment with the positioning of the lenses. We observed Group 2 spend 20 minutes sticking the cardboard tubes together

Figure 7. Group 2's final first model.

end-to-end preventing them from having adequate time to position the mirror and lenses. Consequently, Group 2's final design differed from their original design sketch by the omission of lenses (see Figure 2). Sarah explained to the Research Assistant who was encouraging them to work faster: 'we just realized that we really don't need the lens with it.' After comparing it to the original design sketch, Terese explained 'we'll just rub it out' but on further discussion they decided to write on their first design sketch that they 'didn't use lense (sic)' to communicate their changes to the model (see Figure 2). The final instrument contained the planned number of tubes joined in the desired 'L' shape containing one mirror (see Figure 7). Rewardingly, they had solved the problem they were given with a working model. A number of STEM concepts and processes were apparent in the work of Focus Group 2, including creating a system through which light could travel, choosing appropriate materials, assessing the impact of construction on design; applying understanding about how light travels in straight lines as well as measuring angles. Technological processes also were featured including generating, developing and communicating design ideas when making design solutions (ACARA, 2015).

The analysis showed that during the construction of the optical instrument, students used experimentation for the positioning of lenses, mirrors and tubes resulting in a simpler 'working' model than originally planned in the design sketch. As such, the technological process of creating a system to see a hidden object was at the forefront during this construction stage. This does not discount the importance of the underlying science and mathematics concepts along with the planning of the resources to create a

Table 4. Analysis of students' design sketches ($N = 24$).

Levels	First design (%)	Second design (%)	Difference (%)
0	0	4.2	+ 4.2
1	16.7	20.8	+ 4.1
2	16.7	12.5	− 4.2
3	20.8	25	+ 4.2
4	37.5	27.5	− 10
5	8.3	0	− 8.3

system that resulted in a working model. In such a way, STEM concepts provided the foundation for the design and construction stages. Interestingly, all the final designs in the eight groups were modelled on a periscope using one (six groups) or two (two groups) mirrors. While we acknowledge the limitations on the students' time and choice of resources we were interested in how the engineering design process afforded or constrained students' creative design. Focus Group 1's initial design was much more sophisticated than a simple periscope. Similarly, Focus Group 2 made their model less complex by omitting the lens. We return to this 'narrowing of complexity and creativity' in the discussion section.

Research Question 3: What changes did the students make in the second design?

As explained in Research Question 1, we analysed the students' first and second design sketches and found that the second designs were similar in sophistication to the first designs and did not demonstrate any new applications of science and mathematics concepts.

The data in Table 4 summarise the analysis for both designs:

The data show that there was a slight increase in the number of design sketches coded at Levels 1 and 3 for the second design and a slight decrease in Level 2 and a more noticeable decrease in Level 4. No design sketches were categorised at Level 5 for the second design. This finding highlights an aspect of the engineering design process we did not expect; that is, the redesign process did not afford opportunities for elaboration or extension of science and mathematics concepts applied in the first design stage. Possible explanations for this are in the discussion section.

During this redesign stage, students were encouraged by the teacher to complete their answers in the workbook prior to re-constructing their second design. We analysed the workbook answers from all eight focus groups and found that students' ideas for changing their design predominantly focused on structural changes to improve strength (e.g. adding a stick or longer tubes), weight (e.g. make it lighter), portability (e.g. easier to carry) and visibility (e.g. remove the lens to see the image better). Interestingly, these changes demonstrated consideration of core mathematics, science and technology concepts.

Our content analysis of workbooks was supported with transcript data where students' conversations focused on practical changes as they negotiated changes to the first design through trial and error. For example, in Group 2 they decided not to change the mirror to improve visibility because it would take too much time; however, they negotiated to add more tubes to make it longer to look for 'higher things' (Transcript, p. 26). Students were problem solving by suggesting structural changes to the first design that would enable better visibility of the object. For both focus groups, their second design focused on improving the visibility of the object.

Discussion

Summary of study findings

We were encouraged by the outcomes of this study that showed the Optical Engineering task provided fifth-grade students with a rich learning experience. Accordingly, three main findings make a new contribution to the emerging field. First, the design sketch afforded opportunities for the integration of science, technology and mathematics concepts. Second, students' design sketches enabled them to conceptualise an optical instrument that was translated into a working model albeit with some modifications. Third, the redesign process enabled students to improve physical characteristics of the model. Furthermore, the study identified the importance of the first drawing or first 'design sketch' stage for students actively applying their STEM ideas to the design. This finding pertains to engineering practice – we have identified the salient stage at which students can apply prior knowledge to a design process. We found that 83.3% of students represented scientific understandings about the reflection of light off mirrors through ray diagrams on their design sketches for the first design and 79.2% for the second design. Furthermore, 45.8% of students could accurately measure angles in the first design with a similar percentage in the second design. Such representations are encouraging for teachers who may be concerned that there is a superficial application of science and mathematics discipline knowledge when integration is required in challenging tasks (e.g. Roth et al., 2001).

Contribution to literature

This study shows that fifth-grade students can complete engineering tasks housed in real-world contexts that integrate concepts from science, technology and mathematics contributing to the literature on successful design tasks in the primary years (i.e. Kolodner et al., 2003; Penner, Lehrer, & Schauble, 1998; Roth, 1996; Wendell et al., 2014). We have shown that students can make connections across science, technology and mathematics disciplines whereas prior research has focused on the application of one or two of these disciplines but not all three (i.e. Capobianco et al., 2015; Marulcu & Barnett, 2013). Furthermore, we have contributed to the literature by implementing a new engineering context (i.e. optical engineering), which is novel and to our knowledge has not been researched in primary classrooms.

The use of student workbooks for recording design sketches was successful and provided a structure for stepping students through the iterative design stages. We have contributed to the methodology literature by showing the importance of the design sketch stage as a data source for students to demonstrate their conceptual understanding of the science, mathematics and technology concepts and the detailed coding that is necessary for accurate analysis of the sketches. We created a coding scheme that could be used to code students' design sketches for evidence of core concepts (see Table 2) as a new methodological tool. The coding process required identifying core science, mathematics and technology concepts that provided the foundation for the design of the optical instrument creating a gradation of conceptual understanding for concepts pertaining to optics. As such, we have built on the work by Köse (2008) and Song and Agogino (2004) by combining optical concepts with characteristics of design sketches such as annotations and 2D and 3D representations. Researchers interested in analysing design sketches may use a similar novel coding scheme for analysis. The study has shown the importance of the design sketch stage and the need to emphasise this to children as well as provide adequate time for them to complete the sketches thoroughly. Student workbook answers were useful for analysing their reasons for designs and provided opportunities for students to express concepts in written form. Combining this with the transcripts of group conversations through triangulation gave a much richer picture of the collaborative process through which designs were drawn and how students came to decisions about how to use resources and apply concepts to build a working model. The triangulation of data involved comparing the results across the three data sources (i.e. design sketches, workbook written answers and transcripts) to search for confirmatory and contradictory findings. The analysis of all data led to the finding that the design sketch stage was salient for the application of science, technology and mathematics concepts.

Notwithstanding the successful outcomes, we encourage teachers and students to reflect on students' progress in the drawing stage to ensure application of necessary STEM concepts and to reflect on any problems that may arise such as student fatigue or lack of the requisite drawing skills. As such, teachers can monitor the contribution of the design sketches, workbook answers and student–student discussions to the design process.

The design of similar interventions for the future

We were surprised that the sophistication of mathematics and science concepts did not change from design to redesign and that the majority of groups produced a model similar to a periscope despite more complex designs initially. While students' final models fulfilled the requirements of the task and reflected the work of engineers, that is, using iterative refinement cycles to design and redesign a working model, how to extend students remained of interest to us. Although Group 1 students demonstrated creative thinking, effective skills in sketching designs and strong content knowledge, we reflected on how they could have utilised their complex first design sketch to extend their model beyond a periscope. The engineering design process and the design task structured students' successful outcomes, although there could be modifications to allow more flexibility in the design process. Therefore, we make three suggestions for how similar interventions could be designed in the future, which may afford such opportunities: first, there needs to be flexibility within the engineering design process; second, more teacher scaffolding is needed during the redesign process; and third, the engineering problems need to be designed to allow for differentiation.

First, the iterative nature of the engineering process was successful for stepping students through the design and redesign stages but did not allow students to experiment with complex ideas, or consider alternative routes or test hypotheses. For example, Focus Group 1 were grappling with complex physics concepts (i.e. reflection of light off multiple mirrors) but once they were building their instrument there was no opportunity to stop, revisit the original ideas, experiment with multiple mirrors to see if such a design could work and then apply these findings to the instrument. After they had built their first model, Group 1 students needed more time to look at their original design and ask questions that could be investigated through experimentation before redesigning. Similarly for Group 2, students' experimentation with lenses might have revealed design possibilities for improved visibility of the object. More opportunity to explore the science concepts that appeared in their initial designs may have led to a broader range of final models.

Second, we suggest that the process needs to pause after the first model is built. Teacher scaffolding is required to assess what was achieved in the first design and what needs to be investigated further. Each group can then develop a plan for further science or mathematics inquiries that inform their design. One way to do this is to ask students to identify characteristics of their first design that contributed to the success (or failure) of their first model and how this might be altered to improve their models (Wendell & Kolodner, 2014). Furthermore, group presentations of their models with explanations for design choices can provide further opportunities for scaffolding. Students also require more time to develop designs. Doing design, construction and redesign in one day limited the possible outcomes and was tiring for students (Field Notes). The activity would be better implemented over a few days.

Third, this task could be revised and improved. Providing constraints such as using a minimum of two mirrors may encourage students to trial various combinations. Furthermore, including the cost per resources as well as a maximum cost to build the instrument would model more real-world engineering practices and afford opportunities for students to consider further constraints. Also, the inclusion of lenses in this problem needs to be considered. While lenses may be suitable if students were building a model telescope, it was difficult for students to combine both mirrors and lenses for a working model; however, the inclusion of both enabled rich conversations about the path of light rays (Field Notes) and sophisticated diagrams of optical instruments. The combination of both mirrors and lenses was challenging for this age group.

A further contribution of this study lies in the implementation of engineering design experiences in the primary years; that is, meaningful STEM-integration is possible when students have the prior knowledge to apply to a well-structured engineering design task. Students demonstrated familiarity with core concepts from each of the STEM areas relevant to the task and successfully solved the problem. Our study supports the claim that STEM disciplines 'cannot and should not be taught in isolation, just as they do not exist in isolation in the real world or the workforce' (STEM Task force Report, 2014, p. 9). We encourage teachers and researchers to develop innovative engineering activities to mirror real-world problems; for example, environmental engineering is an exciting new context where students could design housing or parklands for sustainable communities.

Future research

The iterative stages of the engineering process were necessary for students to create a successful working model; however, we have highlighted the limitations with moving through these stages too quickly. Through the development of new engineering activities there is the opportunity for further research to examine how the redesign stage could be used to extend students' use of science, mathematics and technology concepts. This work has begun in the college years (see e.g. Atman et al., 2007; Atman, Cardella, Turns, & Adams, 2005) but is required in the primary years. Furthermore, there is the opportunity for further research through tasks that require students to work within additional defined constraints such as financial and resource limitations that mirror real-world engineering practices. Such opportunities for further research are necessary if engineering education is to be used successfully as a framework for STEM-integration.

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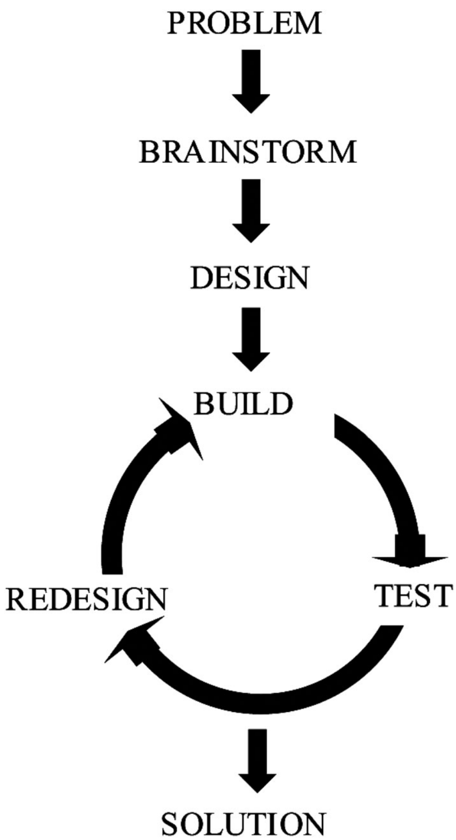
Appendix 1



Adapted from http://www-tc.pbskids.org/designsquad/pdf/parentseducators/DS_TG_DesignProcess.pdf)

Simple Engineering Design Model.

Appendix 2

Just like the engineers and scientists of the past you are going to use mirrors and lenses to design an optical instrument for seeing an object that is hard to see with your own eyes.

Scenario

Your small engineering team (group of three or four students) has been invited to work with optical scientists (physicists) to design an optical instrument that can be used to help you see an object that is difficult to see. The object may be very small, or very far away or it may be around a corner or it may be on top of a cupboard.

Scenario 4

You are playing tennis and your tennis ball is hit very hard by your friend and lands in the gutter of the school building. Design an optical instrument that would enable you to see where the tennis ball has landed.

Scenario 5

The teachers are having a special celebration for a member of staff in the staffroom. You are not invited but would like to spy on the celebration so that you can tell your friends about it. Design an optical instrument that would enable you to see through the window without the teachers seeing you.