Engineering design in the Primary School: Applying STEM concepts to build an optical instrument

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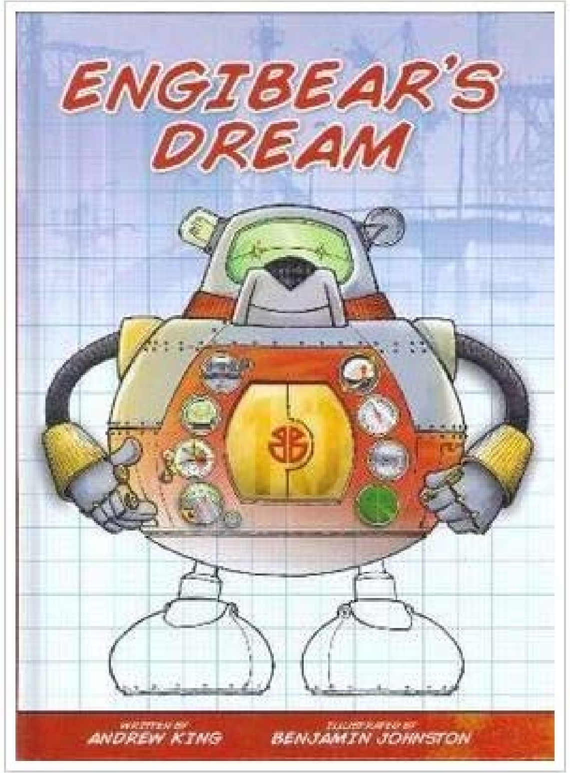
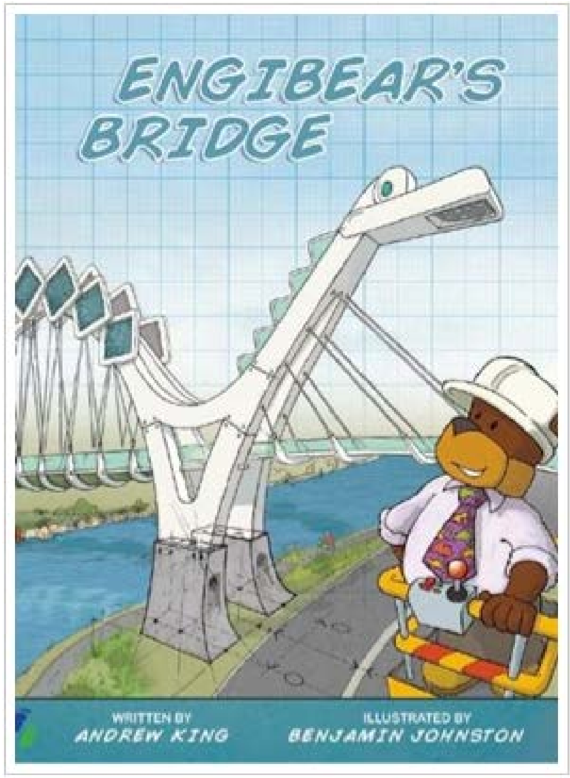
Background

- Three year ARC Linkage grant
- We designed engineering activities and implemented them in five primary schools initially and three schools for the final two years of the study
- Research focussed on students' designs, application of science, mathematics and technology concepts and use of an engineering model
- TMR engineers and QUT engineering students visited students during the activities

(C) Engibear's Dream 2012

Books by Andrew King





STEM across the K-12 Curriculum

- 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 Taskforce Report*, 2014) call for deeper connections among the STEM subjects to mirror real-world practices where **STEM disciplines do not exist in isolation.**

STEM – connections across disciplines

- Equitable representation of the four disciplines through STEM-integrated approaches is difficult to achieve (e.g., English, 2015).

- 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

- 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).

- In the USA the *Next Generation Science Standards* [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).

Scientific Inquiry vs Engineering Design

- Engineering design and scientific inquiry have **commonalities** since they both 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** (Purzner, Goldstein, Adams, Xie, & Nourian, 2015; Wendall, Kendall, Portsmore, Wright, Jarvin, & Rogers, 2014).

Design and Technology vs Engineering Design

- 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).

Engineering Design

- 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).

Challenges designing engineering tasks

- 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 artifact takes precedence (Roth, Tobin, & Ritchie, 2001).

- Well designed activities that enable students to demonstrate STEM connections are needed.

Our study

- 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.**

- 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.**

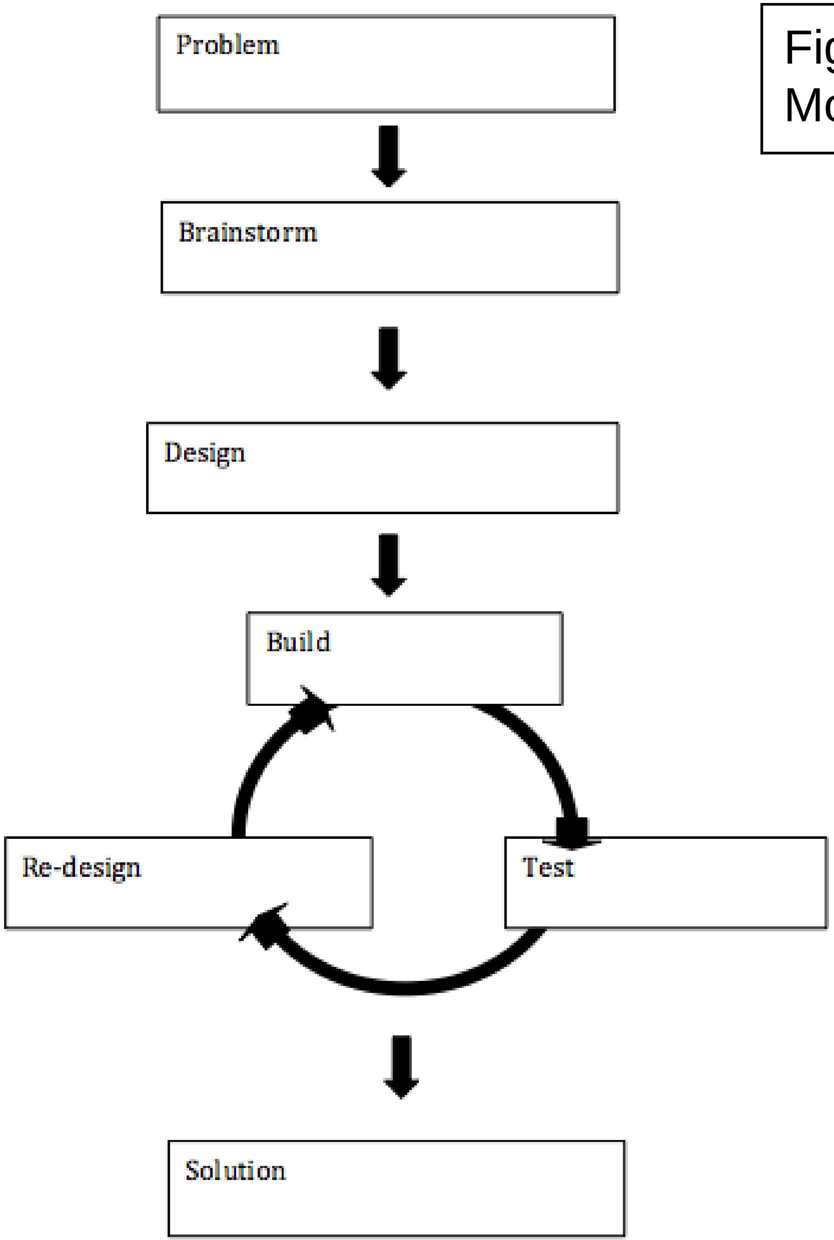


Figure 1. Simple Engineering Design Model

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

Research Questions

- 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?
- 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**?

Conceptual Framework

- *Situated cognition and sociocultural approaches to engineering activities*
- *Learning STEM concepts through design-based approaches*
- *Sketches/Drawings as a tool for representing concepts and designs*

Methods: 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.

Data Sources and Analysis

- Data sources included students' workbooks, video and audio recordings of focus groups, in-class observations and field notes. First, we conducted content analysis (i.e., anlayisng for core science, mathematics and technology concepts) on the workbook responses from the groups focussing on their first and second design sketches by coding for mathematics and science concepts.

- In the workbook analysis we focussed primarily on mathematics and science concepts, however, technology concepts became more apparent when students were building their instruments.

- Similar to the work by Köse (2008), Song and Agogino (2004), the analysis was based on the examination of the data for "recurrent instances" or aspects of the mathematics and science concepts that were present on many of the design sketches. (e.g., the representation of ray diagrams on the sketches) (Wilkinson, 2011, p. 170).

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 the activity, 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.

ACARA

- 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). A
- Also, technological processes were encouraged such as generating, developing, and communicating design ideas when making design solutions (ACARA, 2015).

The Activity

- The activity was designed in two parts. **Part A** consisted of the *Primary Connections* module on Light (Australian Academy of Science, 2012).

- **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.

RQ1

- (1) How are STEM concepts expressed through the process of **drawing** the design sketches?

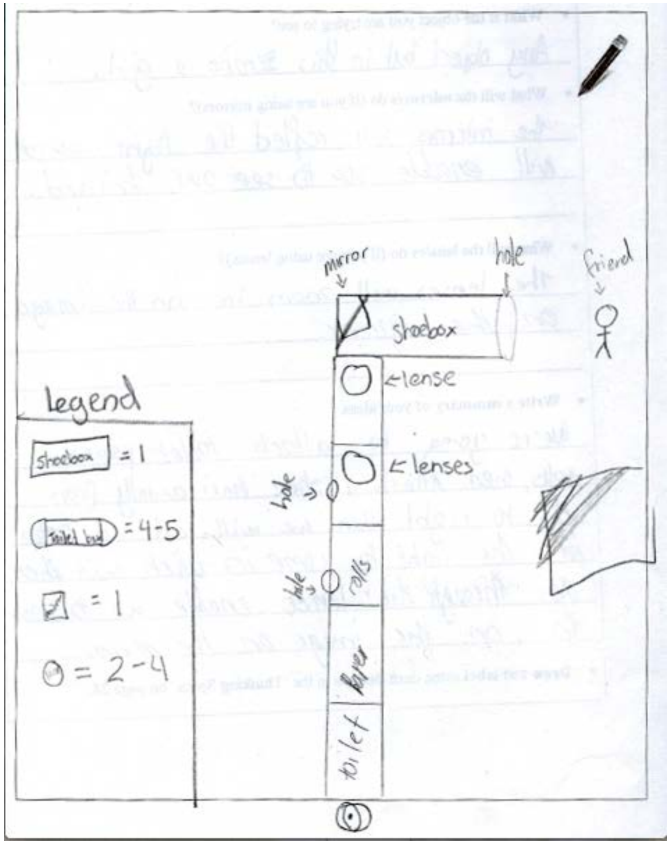
Coding Scheme for Design Sketches

- *Table 1 – 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 labeled 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 45º (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 eye or eye piece to the object, 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 45º 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 45º 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.

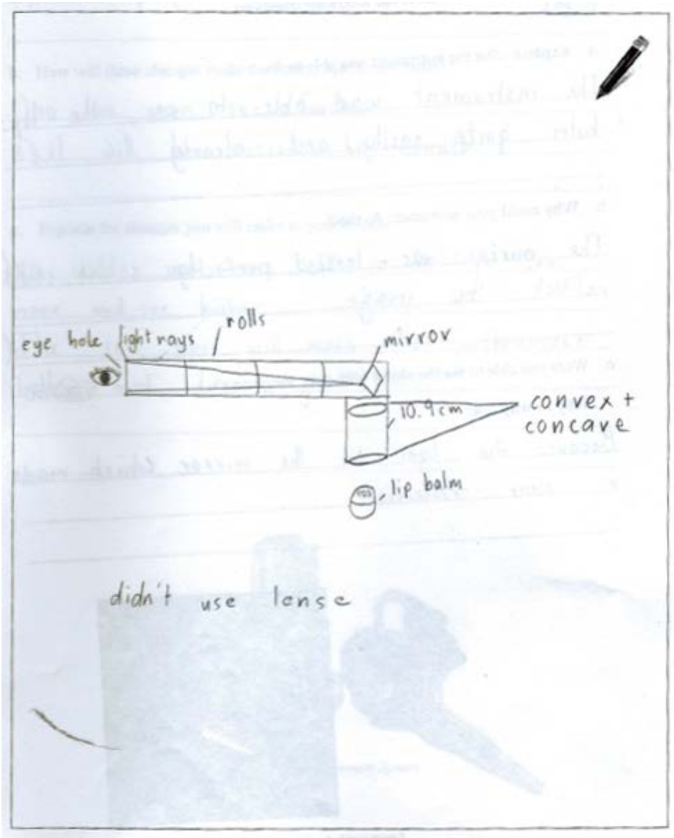
Table for Design Levels

- 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)

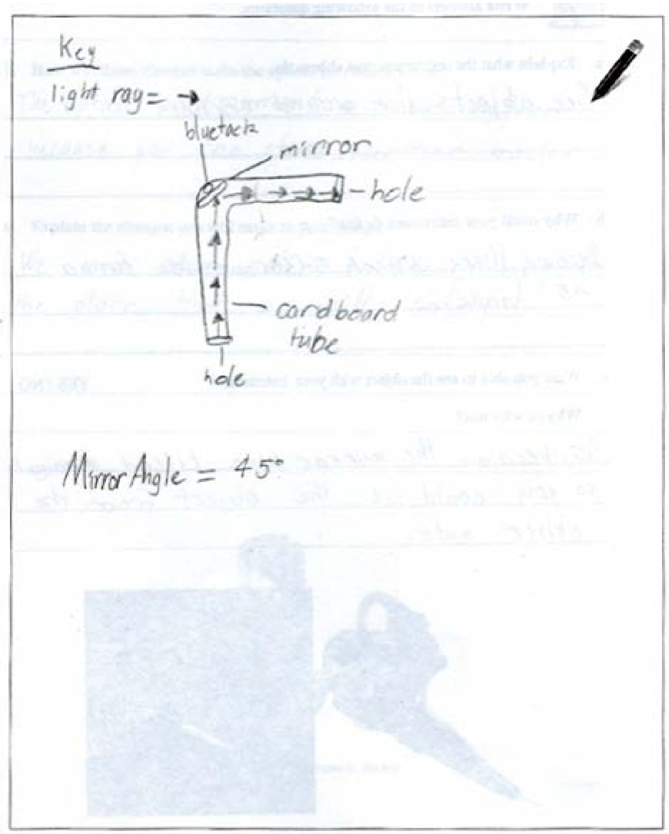
Level One


mirror
hole
friend
shoebox
lense
lenses
hole
hole
Legend
shoebox = 1
= 4-5
= 1
= 2-4
toilet

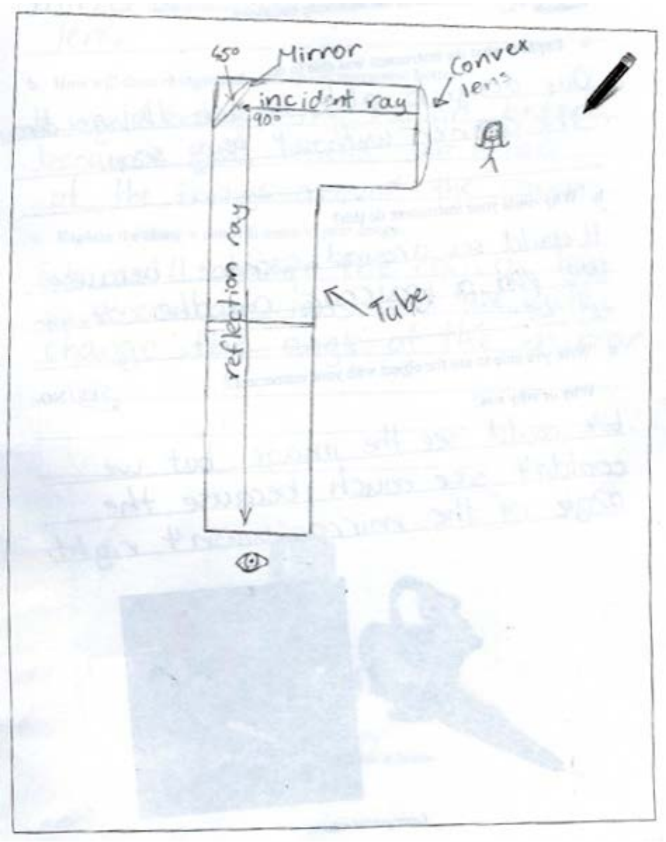
Level Two


eye hole
light rays
rolls
mirror
10.9cm
convex +
concave
lip balm
didn't use lense

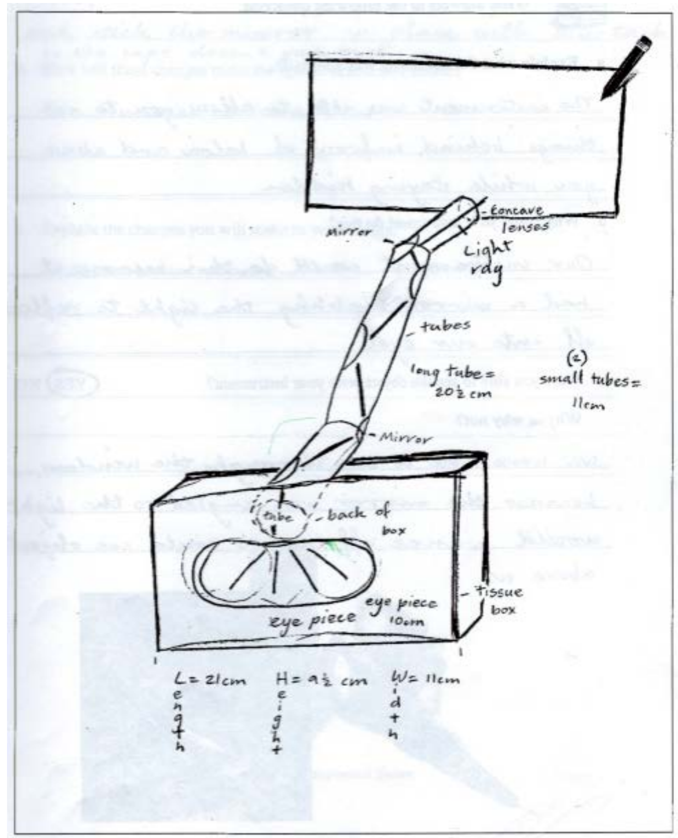
Level Three


Key
light ray =
bluetack
mirror
hole
cardboard tube
hole
Mirror Angle = 45°

Level Four



Level Five



Concave lenses
mirror
Light ray
tubes
long tube = 20½ cm
(c)
small tubes = 11cm
Mirror
tube
back of box
eye piece
eye piece 10cm
tissue box
L = 21cm
H = 9½ cm
W = 11cm

Design Sketches - Results

- In sum, students' design sketches showed 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%). That is, they demonstrated **light reflected off mirrors, travelled in straight lines and 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.**

More Results

- 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.

- The majority of design sketches showed the mirror at a 45^{o} angle for an instrument that was modelled on a periscope (excluding Group One who used multiple mirrors). Also, on further analysis of the mathematical concepts, 45.8% (11) of first **designs included dimensions labeled 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 refraction) and mathematics concepts (measuring angles) was present in these sketches.

Excerpt 1 – Focus Group One 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 realize?	*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*

RQ2

- **How are the STEM concepts applied to the construction of the optical instrument?**

- 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.

- 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.**

RQ3

- **What changes did the students make in the second design?**
- 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.

Table 3 – 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%

Discussion

- We were encouraged by the outcomes of this study that showed the Optical Engineering task provided fifth-grade students with a rich learning experience. There were three main findings:
- **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.

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Publications

- King, D., & English, L. (2016 accepted). Engineering design in the Primary School: Applying STEM concepts to build an optical instrument. *International Journal of Science Education.*
- King, D., & English, L. (2016 accepted). Creating an Optical Instrument through engineering practices. *Teaching Science.*
- English, E., & King, D. (2016 accepted). Engineering education with fourth-grade students: Introducing design-based problem solving. *International Journal of Engineering Education. (submitted for special issue on Current trends in K-12 engineering education)*
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Thank you

- Questions??