Magical Elves and Formulas as a key to technological inventiveness: The case of non-contact distance measurement

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Abstract

Physics students are acquainted with a large set of formulas which they use mainly to calculate numerical answers to end-of-chapter problems. In this paper we aim to demonstrate how purposeful scanning of the stored formulas can help generate inventive ideas for building systems for solving technological problems. The described process takes place within the **Physics and Industry** "Project-Based-Learning" framework for high school physics majors. The students extend their physics and problem-solving knowledge and construct a working model in response to an authentic technological problem in the field of electro-optics. An introduction to the concepts and strategies of **Systematic Inventive Thinking** is used early in the program to enable students to generate creative technological thinking while still in their novice stage. One of the strategies involves "**Magic Elves**" – imaginary creatures which are called upon to perform required functions in the problem solution.
Since many of the student projects involve non-contact distance measurement, we have recently started including this challenge in the early stages of the program. We will describe the instructional sequence we have designed and show several simple inventive applications of physics knowledge.

Introduction -The challenge

One of the challenges facing physics education involves designing learning opportunities which creatively address some of the disturbing results of traditional physics instruction revealed by abundant physics education research during the past 3 decades (e.g. Halloun & Hestenes 1998; Redish et al. 1998; Hammer 2000; Elby 2001; Sherin 2001; Bagno et al. 2008). Some of the predominant weaknesses of prevalent student views are related to the "*Reality Link"* beliefs about the connection between physics and reality and the *"Math Link"* beliefs about the role of mathematics in learning physics (Redish et al. 1998). Sherin (2001) states that "*Connections among concepts, formal representations, and the real world, are often lacking after traditional instruction. Students need repeated practice in interpreting physics formalism, and relating it to the real world*". Tuminaro (2004) claims that *".. the majority of students possess the requisite mathematical skills, yet fail to use or interpret them in the context of physics."*

Physics knowledge is packaged in compact symbolic expressions known as formulas, which describe the functional relationship between physical quantities. Formulas have an "equation" syntax, with one physical quantity on the left hand side of the "equal" sign and the other quantities on the right. Students regard formulas as primary problem solving tools and often use them as calculation mechanisms, inserting "input" values, and deriving the "output" value. Students' selection of the "suitable" formula is often based on surface features of the problem (Chi et al., 1981; Champagne et al., 1982).

High school physics majors acquire a large collection of formulas from studies in mathematics and physics. A printed formula sheet is often provided as a legitimate memory aid. We claim that students' stored formula repository can be used as a resource for inventing creative solutions to technological problems, provided they can be guided towards thinking "outside the box".

In this paper we will describe the design of an instructional sequence implemented within a project-based-learning framework for high school physics majors. Non-contact distance measurement is required in many of the projects, thus offering a relevant and challenging domain for students to improve the Reality and Math links of their physics thinking. The instructional design involves applying structured thinking skills and activation of formal knowledge from physics and mathematics.

The need for reliable non-contact distance measurement exists in a variety of science and technology fields such as traffic control, robotics, automated manufacturing, vehicle safety, helping the visually impaired, astronomy and astrophysics, land surveying, autonomous navigation, acoustic design and ballistics. In antiquity, geometrical methods were employed for calculating the Earth's radius and the distances to the moon and sun. Different physics principles have been employed to design effective and accurate distance measurement on a wide scale range (e.g. Everett 1989; Carullo & Parvis 2001; Yurish 2009). Methods used for non-contact distance measurement include: Time of flight; Triangulation and Electromagnetic induction. 11th grade physics students are unlikely to be familiar with these methods – therefore inventiveness will be required.

The educational context: The Physics and Industry program

The Physics and Industry (P&I) program is a 15 month, extracurricular, accredited program for 11th & 12th grade physics majors. The students meet on a bi-weekly basis at the Davidson Institute for Science Education, extending their physics knowledge into the field of electro-optics and constructing a working model in response to an authentic technological problem in the field of electro-optics. Project topics include optical surveillance of restricted premises, assisting blind persons, preventing vehicle collisions, colour recognition etc.

The novice participants have little technical and technological knowledge and skills, and little experience in applying their physics knowledge. An introduction to the concepts and strategies of Systematic Inventive Thinking (S.I.T) is used to allow the students to generate creative technological thinking while still in their novice status.

Systematic Inventive Thinking (S.I.T)

S.I.T (2005) offers principles and strategies for inventing and designing original & successful solutions for technological problems. Figure 1 shows stages in S.I.T problem solving

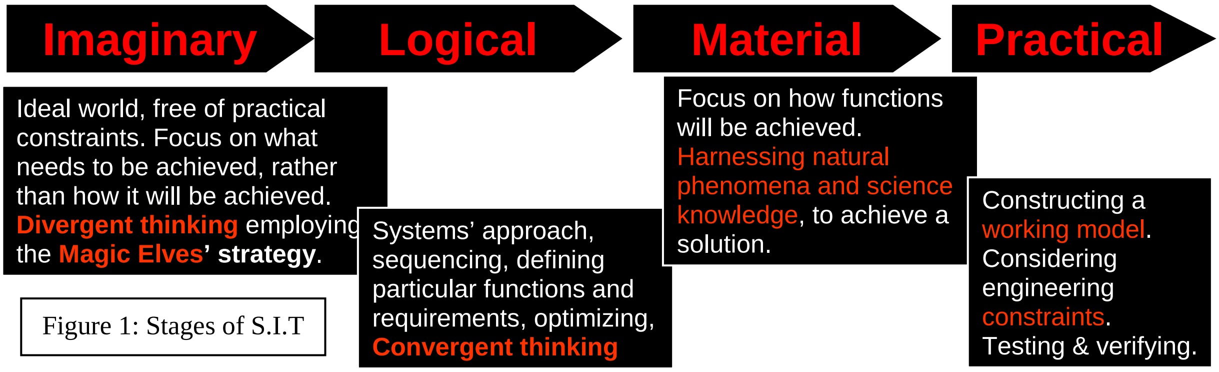
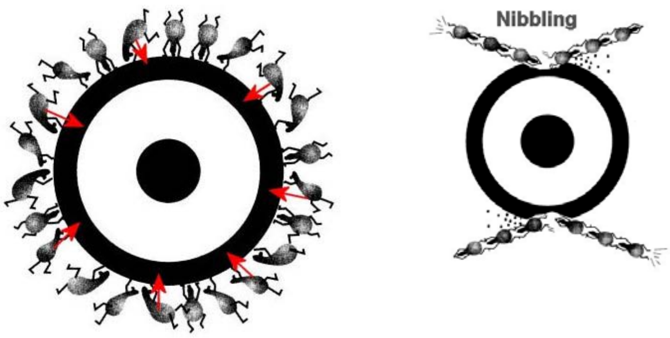


Figure 1: Stages of S.I.T

One of the useful strategies involves "Magic Elves" – imaginary, obedient creatures which are called upon to perform required functions in the problem solution. The elves carry out relatively simple actions dictated by the designer. They can push, pull, link, hover, shout, point, stomp and run using their hands, feet and body. They do not solve problems by themselves. The Magic Elves are invoked in the initial stages of the inventive solution. At later stages the elves' required attributes lead the designer to identify concrete components and materials that can be used to implement the solution model.

Figure 2: Examples of Magic Elves in action



Example (Figure 2): Manufacturing Hazelnut chocolate requires that the hazelnuts are shelled without damaging the inner kernel and without adversely affecting their nutritional value. Magic Elves placed outside the shell can break it by pushing inwards or by nibbling it. Magic Elf diagrams provide a means of visualizing the problem system and suggesting solution methods.

S.I.T is introduced during the first 5-6 weeks of the P&I program in order to develop and practice a creative thinking mode, which is new and exciting for the students. Magic Elves are employed in the context of several technological problem settings such as "Shelling hazelnuts

for chocolate" or "Improved incandescent light bulbs". We also include a "reverse" process "From components to Elves", where the structure of a technological system is shown (e.g. an incandescent light bulb), and students are required to create Magic Elf models that could have been implemented by the given system.
The initial examples of employing Magic Elves involve functions of a qualitative, mechanical nature (pushing/pulling, separating/clinging). Commonplace reasoning, rather than scientific content knowledge is sufficient to create these models. However, more accurate, quantitative functions would be required in the students' selected projects.

The Distance Measurement instructional sequence

The initial introduction of S.I.T occurs several months before students select their project topics. Although Magic Elves are mentioned in some of the intervening activities, students' ability to apply the early ideas in the context of their selected projects has been unsatisfactory. Since distance measurement is required in many of the students' future projects (e.g. Optical surveillance of restricted premises, extending the safety range for blind persons, preventing vehicle collisions), we decided to trigger student thinking on this issue ahead of time. Our expectations were that this would enhance transfer to the project contexts.

Stage 1- Eliciting initial models

The students were required to produce a variety of Magic Elves' ideas and methods for finding the distance between two objects, either of which may be stationary or in motion. The scale of the distance was not specified, and no restrictions of feasibility or practicality were imposed. The goal of having the elves carry out a quantitative measurement meant focusing on the essence of the required measurement (what does it mean to measure distance?) and its quantitative aspects.

Following are some visual examples of Magic Elves' solution models (Figures 3-5):

1. The static ruler model

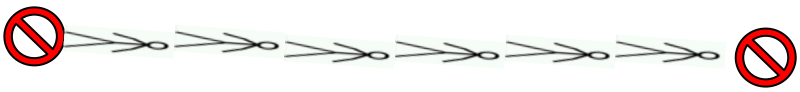


Figure 3: Elves having the same height lie down in a continuous chain until they reach the destination. Counting the number of elves will provide the distance.

This method is an embodiment of the idea that "measurement is a comparison to an agreed unit". This is a contact method, where Elves statically fill the space between the end points. The method of counting Elves or announcing the result is not specified.

2. The dynamic ruler model

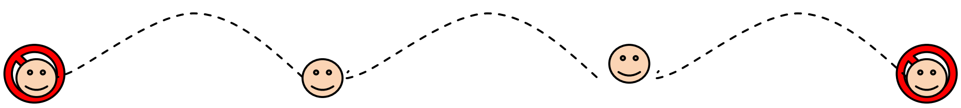


Figure 4: An elf jumps from A to B, progressing a constant distance with each jump. Counting the number of jumps will provide the distance.

Figure 5: An elf whose foot size is given progresses from A to B. Counting the number of footprints will provide the distance.

The dynamic models are similar in principle to the static model, but the space between the end points is traversed rather than filled. There is an assumption of an integer number of jumps or steps.

Our analysis of the students' initial Magic Elf models revealed an almost exclusive focus on one-dimensional solutions, often involving material contact. We also found that ideas concerning how the methods could be implemented in reality included measuring the time light or sound would traverse the distance and calculating the distance using the x=v*t formula. This may stem from students' knowledge of the laser range-finders used by traffic police. Although in principle this is a valid method, it is very difficult to implement since the time intervals involved are very small. Students also mentioned cameras as a means of tracking events and measuring distance, but they regarded the camera as a black-box, without relating the image size to the object's distance from the camera.

Stage 2: Adding dimensions

The following challenge was presented to the students as a trigger for activating the S.I.T problem-solving tactic of "Adding a dimension".

> *"You are standing on the bank of a wide river, and you need to measure its width without physical contact with the opposite bank."*

A class discussion of solution models, including guided hints by the instructors, led to the use of 2-dimensional visualization and mathematical reasoning as shown in figure 6.

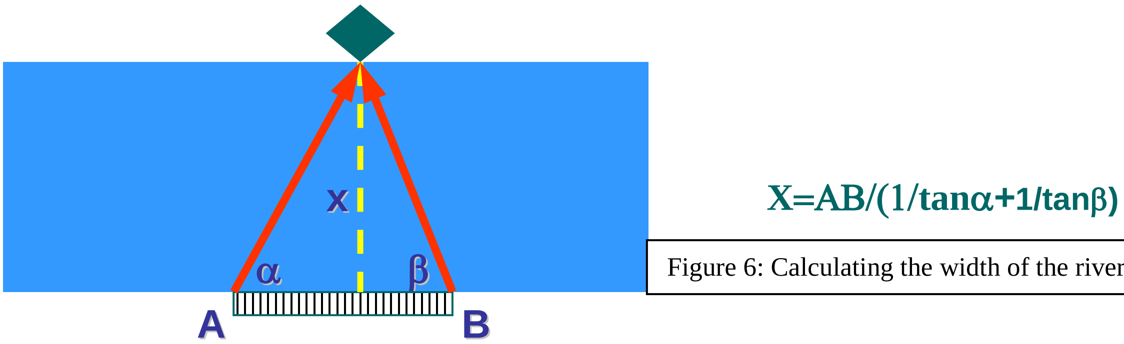


Figure 6: Calculating the width of the river

Thus, the classic triangulation method of non-contact distance measurement (using a baseline and angles) was introduced, enabling students to utilize simple trigonometric formulas to calculate the unknown distance. Clearly, the formula is reduced to the much simpler form $x=AB*\tan(\alpha)$, if β is 90^o.

Representing the triangulation method with Magic Elves is the next requirement. Students draw Magic Elf models for the triangulation method, which necessitate their thinking about measuring angles and storing and transmitting information.

Stage 3 – Activating stored knowledge

In order to activate the "stored formula" resource, students were given the following homework assignment:

- *List all formulas you can find with a length or distance variable.*
- *Express the length in terms of the other variables.*
- *Present ideas how to apply the formulas to design technological methods of non-contact distance measurement.*

Following are some examples of student response (table 1):

Table 1: Formulas with a distance or length variable		
Geometry and Trigonometry	Pythagoras theorem Triangle relations Circle formula	**$c^2=a^2+b^2$** **$a=c*\sin(\alpha)$; $b=c*\cos(\alpha)$; $\tan(a)=a/b$** **$p=2*\pi*r$**
Kinematics	Uniform motion Constant acceleration Free fall Projectile range	**$\Delta x=v*\Delta t$** **$x=x_0 +v_0t + 1/2at^2$** **$\Delta y=1/2gt^2$** **$R=Vo^2*\sin(2\alpha o)/g$**
Dynamics	Elastic force (Hooke's law)	**$F_{el}=-k*\Delta L$**
Work & Energy	Work –kinetic energy	**$W=F*\Delta x* \cos(\alpha) = \Delta Ek$**
Electricity	Electrostatic force Resistance of a conductor	**$Fe= k*q_1*q_1/r^2$** **$R=\rho*L/S$**
Optics	Lens maker's formula Spherical mirror/lens formula Linear magnification	**1/f=(n-1)*(1/R1+1/R2)** **1/f=1/u+1/v** **m=v/u**

Students should be required to convert some of the formulas involving distance, with which they are familiar, into Magic Elf models. For instance, Hooke's law or the lens formula.

Stage 4 – Implementation in project posters

As the program continues the students select their chosen project topics and define the technological problem and requirements of the solution. A poster presentation event takes place about 5 months into the program. It involves displaying a variety of Magic Elf solution models. The effectiveness of the initial exposure to the non-contact measurement issue can be evaluated by the extent creative models based on implementation of physics formulas are manifested in the posters.

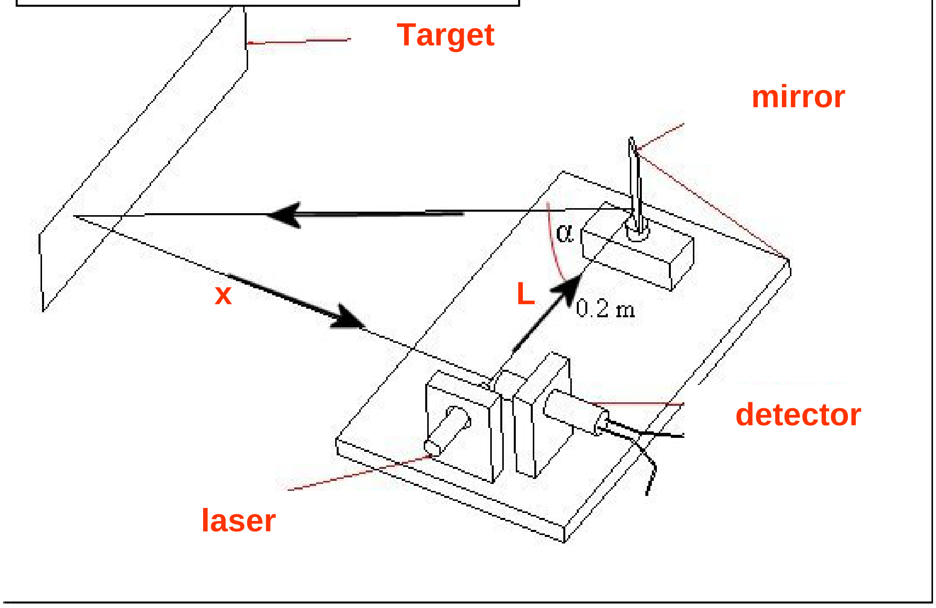
Stage 5 – Implementation in Project Models

Following are several examples of creative **electro-optical** methods of non-contact distance measurement that have been implemented in student projects. These methods were mainly designed by instructors and suggested to students. It is hoped that with the early focus on the issue students will be able to arrive at some of these ideas independently.

1. Laser triangulation has been used for aiding the blind, locating an intruder and safety in reversing vehicles. Figure 7 illustrates the process:

- A laser light source is directed at a rotating plane mirror, placed at a known distance L.
- The light is reflected, the angle of deflection being α.
- The reflected beam hits the target, and is reflected diffusely.
- A directional detector collects light at right angles to the original laser beam.
- When the detector fires, **$x= L* \tan \alpha$**

Figure 7: Laser triangulation system

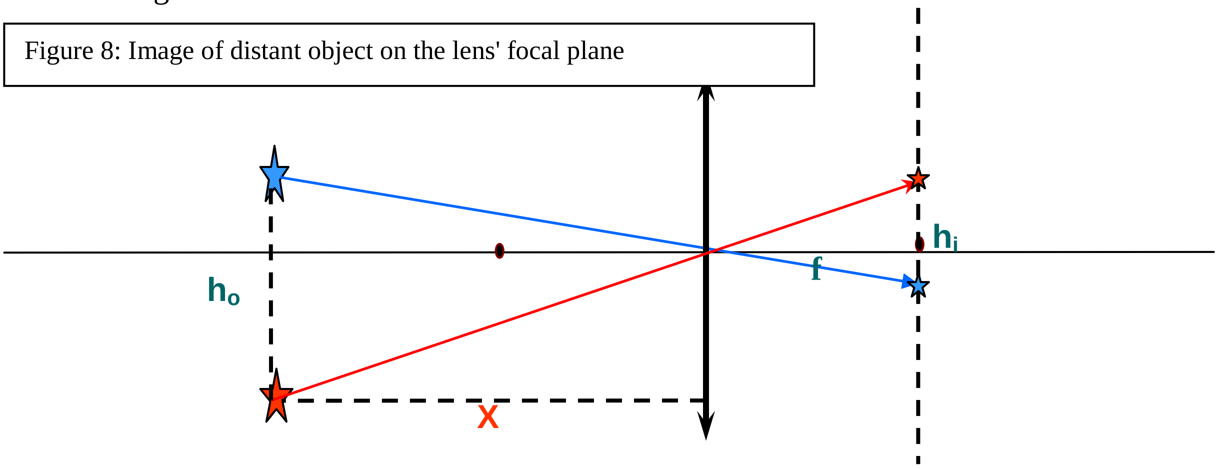


For each target distance X, a specific mirror position is required. To locate a target at an unknown distance it is necessary to vary the angle until the detector responds. The mirror can be connected to the axis of a step-motor rotating at a given angular rate. By recording the data from the detector it is possible to obtain a time-distance sequence and calculate the relative velocity of the target.

2. Lens images can be used for determining the distance to a distant object with a known dimension (Figure 8). The end points of the object either emit light or reflect ambient light. A thin converging lens is placed so that the principal axis is at right angles to the object. The images of the extreme points are created on the focal plane. The object distance X is related to the distance between the extreme images (hi): **X = f * ho / hi**

$\mathbf{h_i}$ can be measured manually or by using a detector array placed along the focal plane. By identifying the extreme detectors that fire at a given moment, it is possible to measure and record changes in the distance.

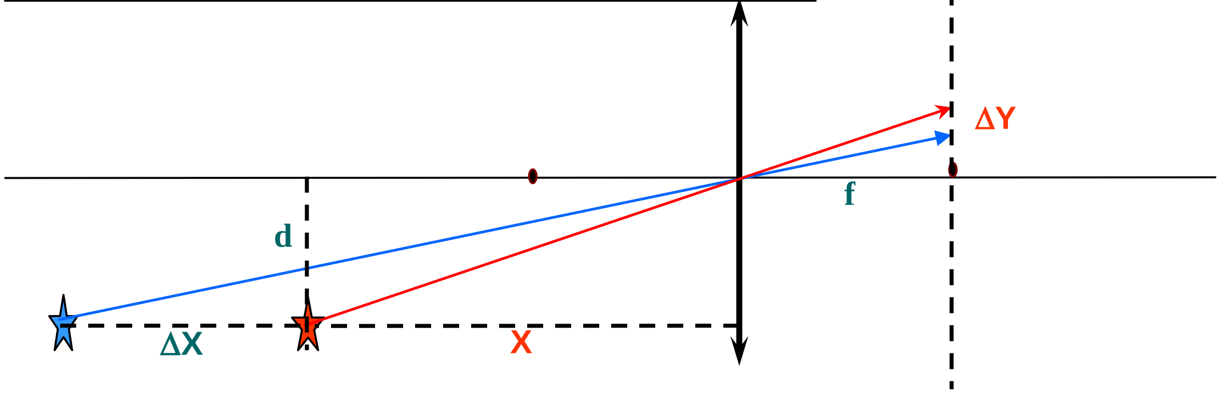
Figure 8: Image of distant object on the lens' focal plane



3. Lens images can be used for measuring the distance between objects, and for calculating relative velocity (Figure 9). Two distant objects are separated by an unknown distance ΔX. A

thin converging lens is placed so that the objects are at positions X and X+ ΔX, on a line parallel to the principal axis, at a known distance d. The images of the distant objects are created on the focal plane at points Y1 and Y2. The further the object, the smaller Y becomes. The distance (X) is related to the image position (Y): **X=d*f/Y**
This method can allow us to calculate the distance between the objects at a certain moment, or the distance traveled by one object during a given time interval.

Figure 9: Images of distant objects on the lens' focal plane



Summary

Sherin (2001) claimed that *"From the point of view of improving instruction, it is absolutely critical to acknowledge that physics expertise involves this more* ***flexible and generative understanding of equations****, and our instruction should be geared toward helping students to acquire this understanding"*

The problem of "Inert Knowledge" has been addressed repeatedly (e.g. Bereiter & Scardamalia 1985, Renkel et al. 1996) with view to creating learning opportunities with the potential of keeping knowledge alive and available for application for problem solving. We suggest that the instructional sequence we have designed for the non-contact distance measurement context which is based on purposeful scanning of the students' formula repository and the subsequent animation by Magic Elf models can be considered as a means of gainful activation of stored knowledge.
We are seeking to improve the instructional sequence so that more students participate in the process and become able to design problem solutions based on their innovative application of their physics and mathematics knowledge.

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