Four Enhanced Science Learning Dimensions: The Physics & Industry Programme

Dorothy Langley,[1,2] Rami Arieli[1] and Bat Sheva Eylon[1]

[1] Davidson Institute of Science Education & Department of Science Teaching, Weizmann Institute of Science, Rehovot, Israel;

[2]Holon Institute of Technology, Holon, Israel

Dorothy.Langley@weizmann.ac.il Rami.Arieli@weizmann.ac.il b.Eylon@weizmann.ac.il

Corresponding author: Dorothy Langley, Langley@hit.ac.il

Abstract The Physics & Industry program is an elective, out-of-school, accredited program for high school physics majors, who meet on a bi-weekly basis for 15 months. The program currently into its 7th cycle, with over 150 graduates, implements a project-based learning instructional approach. Student pairs, coached by industrial engineers, design and construct a working model providing a solution to an authentic, open-ended technological problem, employing principles of electro-optics. The instructional design of the program enhances four learning dimensions as a way of supporting and scaffolding students' efforts and guarding against the undermining effects of conflicting demands and natural attrition during the program: Learning to apply knowledge; Learning to use technological and cognitive tools; Learning to communicate; and Learning to become a member of a community. Our paper provides detailed examples of the activities employed in order to bring about the required knowledge enhancement and presents evidence of the effectiveness of the instructional design.

Key words Project-based learning, Extra-curricular program, Applying knowledge, Technological skills, High school physics,

Introduction

Contemporary physics education faces the challenge of relevance to students' interests and future careers. Euler (2003) claims that "Physics education is challenged to prepare our students to cope with a world of increasing complexity". He suggests that "We have to find more appropriate ways to make physics meaningful to the learners...a positive development of students' interest can be fostered by adequately designed learning environments that focus on authenticity and practical experience."

Mioduser & Betzer (2006) show evidence that project-based-learning contributes favourably to the technological knowledge construction process by high-school high-achievers, and to their ability to design and implement solutions for technological problems, as well as a positive change in attitude towards technology and technological studies. Milgram (1999) shows that a strong relation exists between the focus of high ability adolescents' out-of-school activities and the field of their adult vocation.

Both the challenges and methods of facing them seem quite clear. The question remains whether the answer can be found within the traditional school system. High school physics education operates under many constraints, which prevent the implementation of instruction designed to face the above mentioned and other challenges. This lack is being addressed by academically-based science education centres (e.g. Markovich, 2004).

The Davidson Institute of Science Education provides long-term, accredited programmes for motivated, high-ability science majors. The *Physics and Industry* (P&I) program operates in close partnership with a world-leading electro-optics enterprise, to provide a technologically-focused, out-of-school learning environment. Successful completion of the program grants student 2 of the 5 credits required of physics majors. The 15 month program has been running in its present format since 2004 with over 150 graduates. The project-based program involves students in a variety of theoretical and technological activities leading towards the final product: a working model constructed by student pairs dealing with a real world problem accompanied by a detailed project report. We shall present four enhanced learning dimensions of the program, describe some of the related activities and provide evidence supporting the effectiveness of the instructional design.

Learning to apply knowledge

The initial application range of students' physics knowledge is limited to standard text-book problems. Activities such as explaining observed phenomena, designing a specified system and determining physical features provide opportunities for enhancing the ability to apply physics knowledge.

Explaining observed phenomena

Research has shown that traditional instruction of Geometric Optics is often ineffective for enabling students to explain and predict optical phenomena related to image observation (e.g. Goldberg & McDermott 1986). Activities involving observation, exploration and theory-based explanation are intended to engage students mentally and physically in applying their formal knowledge. Fig. 1 shows two solid glass rods placed in transparent containers containing water and glycerol, respectively. The glass rod can be seen in the water but is invisible in the glycerol. When the glass rod is withdrawn from the glycerol it "re-appears".

Fig. 1 Why does the glass rod vanish in glycerol?

Designing a specified system

In the technological world, electrical, mechanical and optical systems represent physics knowledge based, designed solutions of real world problems. Students require practice in this form of knowledge application. This is achieved through instructional activities named "mini projects" (Langley, Arieli & Eylon 2006).

Mini-projects are short (3-4 hours), semi-structured activities. Student teams are required to design and construct a working system solving a given technological problem and to verify that their product conforms to the specifications. The mini-project worksheet contains the technological problem description, expected product performance, equipment specifications and available options and requirements for the detailed team report. For example the problem description of the "Seeing around obstacles" mini-project: Sometimes it is necessary to see around opaque obstacles or to see without being seen. Product specifications: 1. Create an upright image. 2. Allow the observer to see the image in the absence of a direct line of vision. Available equipment: 8x8 cm front reflecting plane mirrors, cardboard, adhesives, scissors, etc. Fig. 2 shows a sample product of the mini-project.

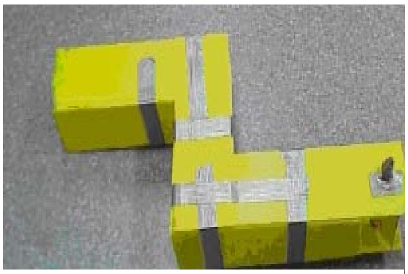


Fig. 2 Sample mini-project product

Determining physical properties

Scientists and engineers apply physics principles to determine properties of components (e.g. resistance of a conductor, focal length of a lens or wavelength of light). Physics principles can also be used to calculate system variables such as distance to a target or velocity of an object. In contrast with end of chapter questions with given system data, our students are required to select a strategy, decide on the required data, perform the necessary measurements and carry out calculations, taking into account experimental error.

Fig. 3 shows the set up for measuring the focal length of a divergent lens The students are given a set of 4 lenses (2 convergent, 1 divergent and a Fresnel lens), and are required to find their focal lengths within one hour. The worksheet refers to the relevant definitions and formulas and summarizes the different methods for determining focal length. The equipment trolley offers rulers, small light bulbs, paper screens, and metal optical benches to which the equipment can be attached by magnetic strips.

Finding the focal length of the divergent lens is the real challenge for which students need to integrate data with theory of lens' systems.

Fig. 3 Measuring the focal length

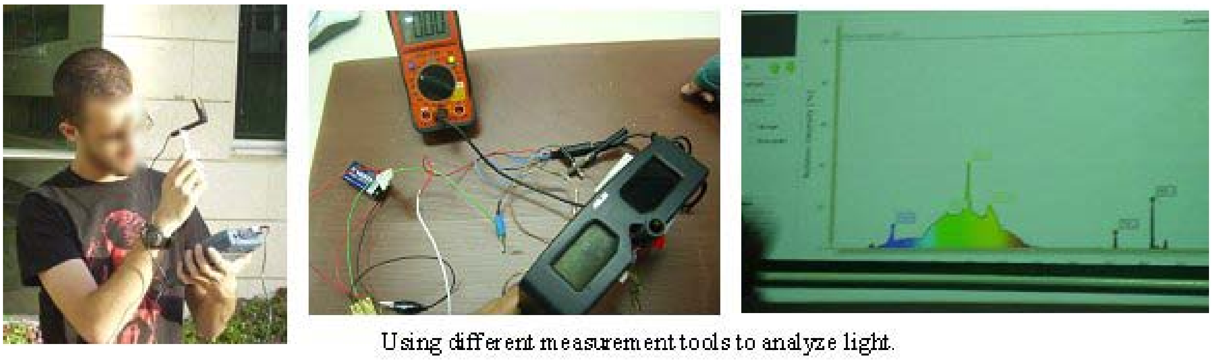
Learning to use tools

In view of the students' limited initial skills opportunities and modelling are provided for using common, as well as more advanced technological and problem-solving tools.

1. Basic technical tools, such as glue-guns, saws and screw-drivers (Fig. 4).

Fig. 4 Students using technical tools

2. Physics' measurement instruments including voltmeters, ohmmeters, power meters and computer-based measurement such as data-loggers and audio analysis software. Freely available audio analysis software (e.g. Goldwave or Audacity) is used to sample changes in light intensity. This enables measurement of high frequency phenomena and motion detection and analysis (Fig. 5).



Using different measurement tools to analyze light.

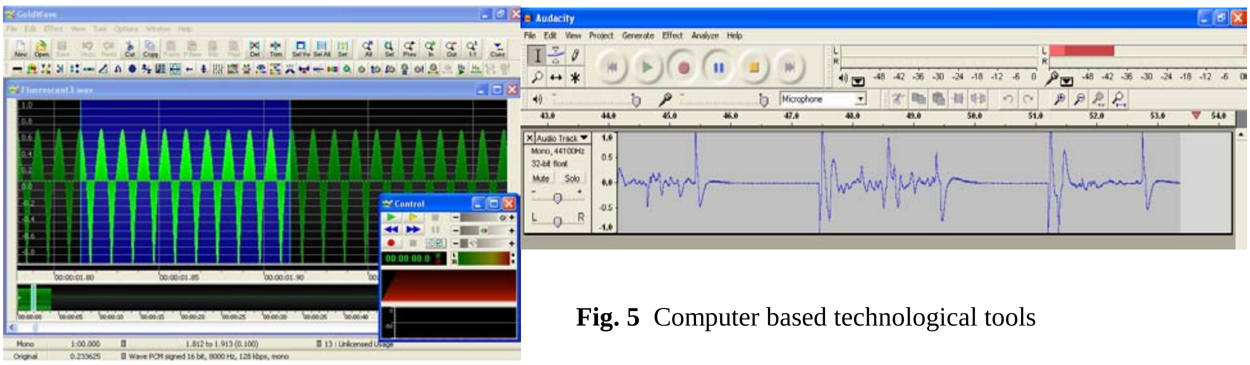


Fig. 5 Computer based technological tools

3. Cognitive tools

Software tools (simulations, spreadsheets, word processors and graphic software) facilitating visualization of systems and phenomena and extending cognitive abilities are employed. The Visual Quantum Mechanics and PhET simulation packages are used in several contexts. The Visual Quantum Mechanics simulation (Fig. 6) is used to help students relate observed spectral phenomena with the basic notion that light emanates from matter and the quantum nature of light.

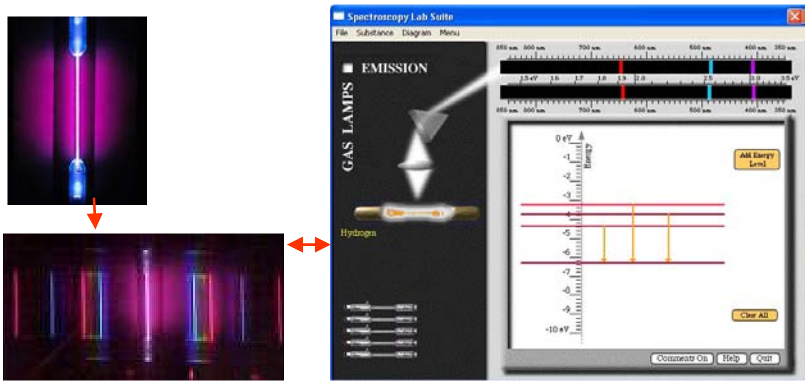


Fig. 6 Visual Quantum Mechanics simulation – Gas discharge lamps

Systematic Inventive Thinking (S.I.T) offers principles and strategies for inventing and designing original & successful solutions for technological problems. S.I.T problem solving involves several stages:

- **Imaginary stage**: Ideal world, free of practical constraints. Focus on what needs to be achieved rather than how it will be achieved. **Divergent thinking** employing the **Magic Elves'** strategy (Fig. 7).
- **Logical stage**: Systems' approach, sequencing, defining particular functions and requirements, optimizing**.**
- **Material stage**: Focus on how functions will be achieved, harnessing natural phenomena and science knowledge to achieve solution.
- **Practical stage**: Constructing a working model, considering engineering constraints, testing, verifying.

The "Magic Elves" are imaginary beings with unlimited abilities - within the laws of nature. There is an unlimited supply of elves and they have no physical needs. Different elves can perform different functions. However, they have no initiative of their own – they only do what the designer commands them to do.

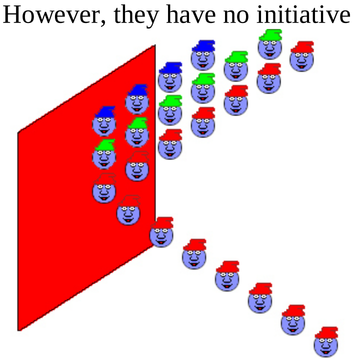
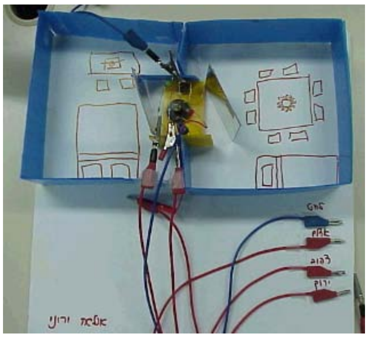
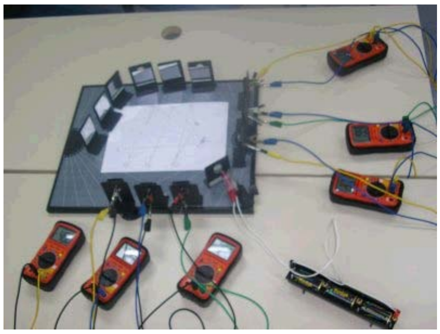


Fig. 7 Magic Elves representing RGB components of white light, hit a red material and only the R elves are reflected. Different solutions can be represented by different ways the G&B elves are subtracted from the incoming beam, or by different ways the R elves are re-created and emitted.

Learning to communicate

The program provides many opportunities for verbal, oral and graphic communication. Some of the routine avenues involve accessing the program web site for information updates and posting messages, communicating with course leaders by email, and preparing and submitting experiment reports and homework assignments. Following are some detailed forms of exercising different communication modes.

Photographically documenting events and systems (Langley & Arieli, 2010) enables repeated viewing of the physical event, possibly from several angles, thus transcending the limitation of visual memory and promoting reflection. In the P&I program, digital photography is employed extensively, both by the course leaders and by participating students. Photography by course leaders is intended to model systematic documentation, promote a sense of community, provide a quality photograph repository and collect materials for research and public relations. Digital photography by students (Fig. 8) facilitates documentation of experiment equipment for preparation of reports, and for future replication, documentation of experiment results, and project performance away from the lab, capturing what the eye sees in optical systems, documentation and tracking of project progress, preparation of graphic content for project report and homework assignments, capturing teacher explanations from the whiteboard, or from a mentor’s sketch, communication with an absent partner, or distant mentor and finally documenting situations for personal satisfaction and future sharing with peers and family.

Measuring focal length of a Fresnel lens. 	Student capturing the set up for a triangulation measurement. 
Capturing the product of the illumination mini-project. A mixture of actual apparatus, and diagrammatic representation, of two rooms with different lighting requirements. 	Demonstration set up of a basic model for detecting an intruder into a secure area, using a laser beam, a diffraction grid, plane mirrors and solar cells connected to voltmeters. 
Fig. 8 Photographic documentation of technological set ups	

Preparing, presenting and evaluating posters

About 6 months into the P&I program, students participate in a "poster session", during which they present and defend their initial ideas for their projects (Fig. 9a and 9b). The poster presents information about the team, project topic, technological problem context, requirements of the future solution, functions that need to be performed in the system, and 7-10 Magic Elves' solutions utilizing SIT principles .

Fig. 9a Students setting up their posters

Fig. 9b Presenting poster and defending ideas during the peer and expert evaluation phase.

Following are some results of the 2010 poster session questionnaire (N=32). The results (Fig. 10a, 10b) indicate that students considered the poster presentation event beneficial both motivationally and cognitively.

Aspects of evaluating peers

(1=very little, 2= to a certain extent, 3=greatly)

- It was difficult to evaluate peers' work.
- The evaluation enhanced my understanding.
- It was interesting to view projects and models.

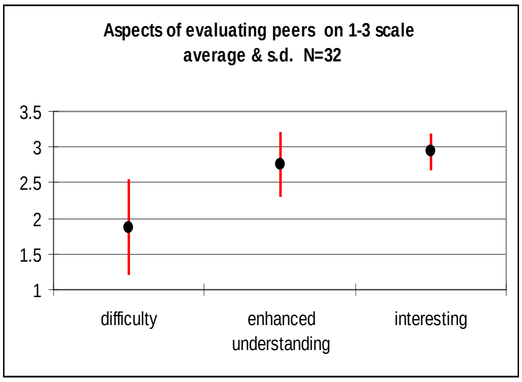


Fig. 10a Students attitudes towards evaluating peers

Aspects of being evaluated by peers

(1=very little, 2= to a certain extent, 3=greatly)

- It was difficult to present my project and models.
- Presenting my poster enhanced my understanding.
- It was interesting to explain my project and models.

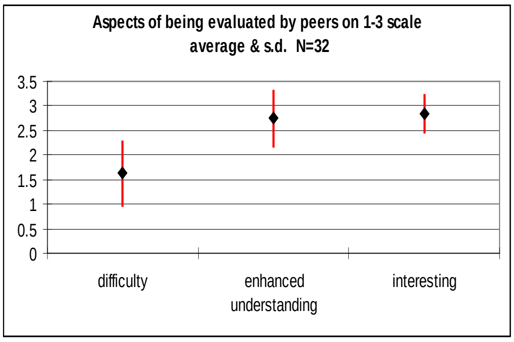


Fig. 10b Students attitudes towards being evaluated by peers

Presenting products to peers and experts occurs several times during the program e.g. mini-projects and initial models (Fig. 11). Each team describes the technological problem it has addressed, the principle behind their product, the set up and components and finally demonstrate that the product fulfils the requirements and has various merits. Members of the audience pose questions to which the team responds. Peer-evaluation of the presented products is carried out on distributed forms and the results are conveyed to each team.

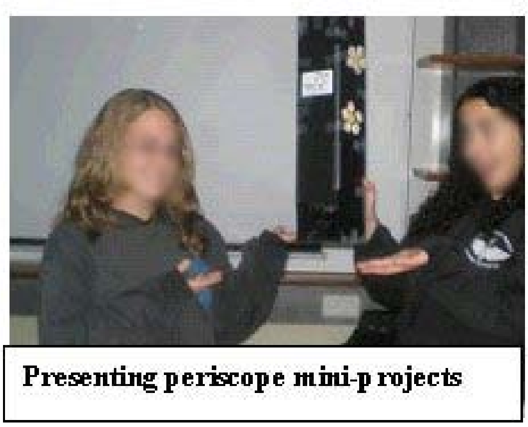


Fig. 11 Presenting projects

Explaining the project to internal and external evaluators

The evaluation sessions requires the project team to define the problem, describe the physical context and its requirements, explain the physical principles employed, demonstrate the functioning of the model and explain the role of each component. Finally, the team evaluates the model and suggests improvements. For the external evaluation the teams often prepare a power-point presentation, to which they may refer during the oral exam (Fig. 12).

Fig. 11 Explaining to evaluators

Composing a project report

The project report consists of an executive summary and a detailed report explaining the technological problem in context, the development process of the model starting with the imaginary Magic Elves, and progressing through the different stages until the final model. The physics principles involved in the project are explained as well as the experiments that were carried out in selecting the components. The report also includes a reflective summary in which the project team defends and critiques the decisions taken, and suggests improvements of the final product.

Students' comments indicate that producing a lengthy, structured report is a unique experience of which they are very proud.

Fig. 13 Interacting with professionals

Learning to become a member of a community

The P&I participants, who come from different schools, are helped to develop a sense of belonging to an "elite" community. The students meet and collaborate with professional adults at work (academic teachers, doctoral students, technicians, engineers and scientists), as well as with P&I graduates studying for engineering degrees Fig. 12). The program is organized around 6 events, each marking a milestone along the road from novice participant to accomplished graduate: opening ceremony, tour of a high-tech industry, poster session, initial model presentation, final evaluation and graduation ceremony. The sense of belonging is reinforced by the within-team and inter-team interactions, and the shared photo repository.
The strong partnership with the leading Electro-Optics industry is consolidated through invited lectures, a tour of the plant and coaching by the engineers.

Supporting evidence for the instructional design

1. Students successfully construct the working models they designed. The average grades on the final external examination are above 90%.

Table 1 Average final grades in matriculation units

Program year	Graduates	Projects	Radiation & Matter unit	Lab unit
2004-5	28	15	95.7	97.1
2005-6	12	7	97.4	98.5
2006-7	21	12	94.7	96.3
2007-8	24	12	94.5	96.4
2008-9	21	12	94.0	95.1
2009-10	24	12	94.6	99.0

A variety of examiners have commented favourably about the high level of the products and the level of scientific discourse students displayed.

2. After the initial settling period, 80% of the group persevere and complete the program. This is a non-trivial achievement since the students are not relieved of their school physics duties up to the final evaluation and could gain the same credits at school. Also participation in the program involves payment, self-transport and investment of considerable time over a long period.

3. Positive reflective testimonials by students, teachers, engineers and examiners

Student testimonials in the project report reflective paragraphs indicate the awareness of the programs benefits:

- *The program helped us understand more genuinely what physics and its application meant. We were able to emerge out of the school routine of lessons and books to which we were accustomed.*
- *We learnt how to apply our knowledge. We learnt how to integrate knowledge from different domains. We learnt how to overcome criticism and become more creative.*

Teacher Views

Over the past 6 years, we have repeatedly seen that the physics teachers enthusiastically encourage their high ability students to join the program and persevere in it. Teachers comment on the added-value the program contributes to students' knowledge, skills and confidence.

Leading engineering industry support

The P&I program (in its various forms) has been supported by El-Op, a world leading electro-optics industry. This support, which indicates the value the high-tech industry attributes to the program, is manifested in many ways including participation of engineers in the project coaching process, opening the plant for a structured guided tour, and responding favourably to requests for lectures.

4. Mid-program reflective questionnaire affirms students' satisfaction with the program components. Following are some results for our 2010 cohort (n=32).

a. Overall impression

Overall I am satisfied with participating in the program. According to my impression so far I would recommend participating in the project to my friends.
4=strongly agree, 3=quite agree, 2=quite disagree, 1=strongly disagree
Results: Average= 3.4, s.d.=0.62

b. Satisfaction with various aspects

Table 2 Satisfaction with domains

Aspect	average	sd
Geometrical Optics content	3.3	0.8
Electro-optics content	3.0*	1.3
SIT content	3.7	0.5
Technical support	3.5	0.7
Staff attitude	3.5	0.6
Atmosphere	3.7	0.5
Variety	3.3	0.8

The data indicate a widespread, high degree of satisfaction with the main aspects of the program (table 2). The low rating for electro-optics was related to little exposure at that stage.

c. Favoured activities

Table 3 Ranking activities

Rank	Activity
A (top)	Experiments
B	Tour of industry, Poster preparation and presentation
C	SIT, Team work
D	Project topic lectures, Demonstrations, Learning theory
E	mini-projects, computer based lab, Project design

The data show the preference for hands-on and minds-on activities (table 3).

d. Effect of program aspects on knowledge development

4=very large, 3=quite large, 2=quite small, 1=very small

Table 4 Knowledge Development		
Knowledge development factors	average	s.d.
Application of physics principles	3.6	0.62
Demonstrations	3.3	1.06
Computer simulations	2.9	1.07
IT communication	3.1	0.98

The data indicate that students considered the applicative, practical aspect of the program as having the main impact on knowledge development (table 4).

5. Long term effects

Over the past 6 years we have gathered consistent (if anecdotal) evidence about the long term effects of the P&I program:

- Recent-graduates respond positively to the request to take part in evaluating the new class's posters. We are impressed with the seriousness and knowledge they display as they pose questions and suggest changes.
- Graduates who are studying for university engineering degrees return to act as project coaches.
- Graduates continue communicating with the project leaders about innovative technological ideas they have.
- Exceptional graduates are accepted as research assistants with leading scientists or are placed in prestigious positions in their army service.
- Family ties: so far 8 younger brothers or sisters joined the program following their older siblings.

6. Graduate survey

During 2011, a phone survey was conducted amongst a small sample of the graduates of the 2004-2010 Physics and Industry classes (14 males and 5 females). 7 graduates were engaged in academic studies after their army service; 8 were in the army (conscription and regular service); one was working at the science park after his army service; and 3 were still in high school.

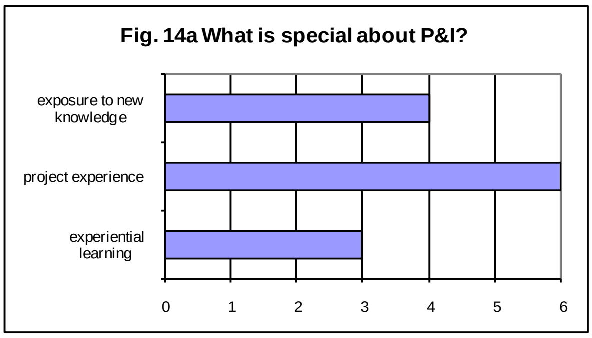
- Reasons for joining the program

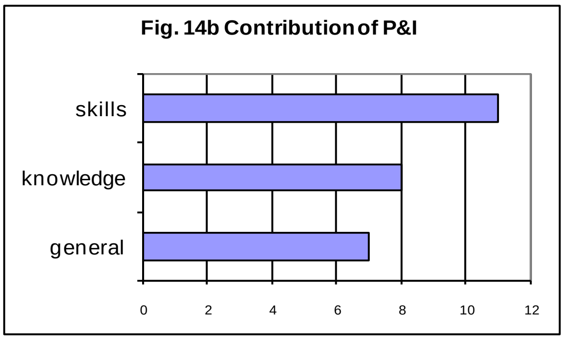
  The main attraction was the content that sounded more interesting than the regular school physics. Over half the sample stated that the main motivation was the interest and love of the subject. The challenges the program presented was also mentioned. Creditation was mentioned by 21% as additional motivation.
- Contribution of the program

  The graduates were satisfied with their choice and the effort they had invested in completing the program. 15 of 19 stated they would recommend participation to their friends. All the graduates mentioned extension of theoretical and practical physics knowledge (Fig. 14b). They also mentioned the acquisition of a variety of skills such as project management, problem solving and hands-on scientific inquiry skills (Fig. 14a). The acquired knowledge and skills had proved useful for their future academic and military careers.

  The change in cognitive thinking patterns following the Systematic Inventive Thinking course was considered a major contribution by all the graduates.

  The program contributed to helping students define their academic identity and future. 8 stated they would study physics and engineering and another 3 selected medicine. The encounter with the practical side of physics along with the face to face interaction with industry and engineers, scientists and advanced degree students opened a window into the worlds of industry and academy. This is an experience not open to many high school students.





- Main difficulties
  Most of the interviewees did not remember or mention any particular problems they had encountered. A few mentioned the pressure of assignments during the second year, because of the regular school work and the need to complete the project during the period of critical exams at school. A few graduates pointed to the unsatisfactory support by the course leaders and problems with partners leaving. Some of the interviewees would have liked better social bonding with other participants.

Summary

The P&I program represents an instructional framework created to address the challenge of extending the learning experiences of high-ability, high school physics majors towards the realm of technological applications of knowledge. It conforms to the model of a learning environment that fosters the productive use of acquired knowledge and skills since it "confronts students with challenging, realistic, problems and situations that have personal meaning for them and are representative for the kind of tasks they will encounter in the future" (De Corte, 2003). It also displays several of the desired attributes of science learning environments proposed by Euler (2003):

- Getting in touch with science and technology in the work place.
- Personal contact with students and scientists.
- Creating opportunities and stimulating environments to interact with authentic problems from science and technology that pose a certain degree of challenge.
- Working on problems that show cooperative and collaborative aspects of projects in science and technology.

The described instructional design has been developed over the past 7 years, and it will continue to evolve in response to additional challenges such as dealing with the recruitment and perseverance of female students and the integration of advanced technologies.

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