Scientific Visualisation: Linking Science and Technology Education through Graphic Communications

RESEARCH

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Abstract

Scientific visualisation is a new curriculum in the technology education area in North Carolina, USA. The goal of this two-course curriculum is to help develop students' ability to communicate technical and scientific information to a variety of audiences. A historical context is set to help explain the development of this curriculum. The curriculum's unique application of the design process to visualisation methods and its emphasis on the use of science and technology concepts for visualisation topics are discussed. How curriculum is implemented in the classroom and an example activity are outlined.

Introduction

Scientific visualisation is a new curriculum in the technology education area in North Carolina, USA. The development of this curriculum has been motivated by a belief that graphics, as a means of communication, has been growing rapidly worldwide, but has been largely neglected as a course of study in US secondary schools. This curriculum was designed to help rectify an undue emphasis of verbal/written literacy over graphic literacy.

The goal of this two-course curriculum is to help develop students' ability to communicate technical and scientific information to a variety of audiences. Graphic design principles, along with 2D and 3D graphical techniques, are used to represent both empirically and theoretically derived data in visualisations. In addition, visualisations can also be created representing non-data derived representations of science and technology concepts. Integrated into this new curriculum is the use of the design brief to promote the structuring of classroom activities around individual and group exploration of effective means of communicating scientific and technical information. By its design, this curriculum also integrates mathematics, science, and technology in a single curriculum. In introducing the curriculum, how it relates to current thoughts in educational theory and standards will also be outlined.

Scientific and technical visualisation curriculum

Historical context

The use of graphics to convey scientific and technical information is as old as science and technology itself. Through much of this period, the graphics were created through manual methods: ink or pencil on paper with or without mechanical aides such as compasses and straight edges. In more recent times, a class of professional graphicians has been used to create scientific and technical graphics used in mass-distributed media, such as newspapers and magazines. Where science and technology was the topic of these graphics, the approach was to appeal to a diverse, lay audience. Viewed in this context of mass media communication, scientific visualisation can be thought of as a natural offshoot of the traditional graphic arts curriculum.

The 1980s also brought into use, by scientific and technical professionals, the colour graphics computer workstation. In combination with custom-written programs, graphics workstations were used to produce graphic visualisations of the masses of data being produced by a new generation of supercomputers (Friedhoff and Benzon, 1989). During this period of the late 1980s and early 1990s, lower cost computing power meant the expansion of visualisation in scientific research to the desktop computer (Keller and Keller, 1993). Still, many of these tools were not much more than computer source code libraries. In this context, these visualisations were produced by scientists and programmers for themselves and their peers rather than a wider audience.

The mid-1990s saw the growth in affordable 2D and 3D graphics tools that had the potential of being used by diverse groups of students and educators. Typically, custom programming to produce visualisations was no longer needed. Still, the use of this new generation of visualisation tools had to be put into a framework, so that users would understand how to use the tools to effectively communicate with others. Part of the framework was provided by theorists trying to understand how best to support communication graphically in an increasingly information-burdened society (Bertin, 1983; Tufte, 1983). This framework was brought into a learner-as-designer practice and a computer technology-based laboratory to create the current scientific and technical visualisation curriculum.

Background of the curriculum

For the past four years, the authors have met with teachers and administrators from North Carolina (USA) Public Schools to develop and improve a new sequence of courses in scientific and technical visualisation (Carolina, 1997). The main goal of these courses is to teach technical graphics to a diverse audience of high school students. The courses are designed to reflect a broader application of computer graphics techniques in the workplace and represents a rich area in which technical graphics teachers at all levels of education can be involved. These new technology education courses complement,

rather than replace, more mainstream technical graphics courses in architectural and mechanical drafting currently being taught through vocational education. This curriculum resides in a communications technology area, providing a clear content focus for the use of information technology and computer graphics technology to communicate scientific and technical information.

A course in scientific visualisation was first taught at North Carolina State University in 1990 (Wiebe, 1992). This course, intended for college students in any year and from any degree path, was developed as an exploratory course to examine alternative methods of developing visualisation and technical graphics skills to a wide audience of students. What was soon realised was that material could be developed and taught at a number of different educational levels. At the high end, graduate students could use scientific visualisation techniques to explore data analysis techniques in their discipline-specific areas. Of more interest was moving the scientific visualisation curriculum down to the secondary school level.

Momentum for a high school-level scientific visualisation curriculum developed out of a revision of the complete high school technical graphics curriculum developed by the same team now working on the scientific visualisation curriculum (Clark and Wiebe, in press; Wiebe and Clark, 1998). As university professors, we saw a need for students coming into higher education with stronger graphic literacy and visualisation skills. In addition, we saw this curriculum as being a perfect example of how science and technology education can be integrated; a long standing goal in technology education (Basu, 1997; Conte and Weber, 1999; ITEA, 2000; Salinger, 1994; Wicklein and Schell, 1995). It became clear that scientific visualisation could offer an expanded track in communications technology that was uniquely different to what was currently covered in technology education, technical graphics, or other related curricula.

As a whole, this curriculum has a number of unique elements that sets it apart from other tracks in technology education or more traditional vocational programs as they are taught in the US. First, unlike many technology-related curricula, science and technology play a central role in both the creation of the product and the product itself (Friedman and diSessa, 1999). Not only is computer technology used in the creation of the visualisations, but the visualisations have as their subject matter science and technology topics. Secondly, the design process – as it is applied in the real world – plays a central role in the curriculum. Neither the path to a design solution nor the ultimate solution is predefined for many of the activities in this curriculum. Finally, this curriculum is uniquely multidisciplinary. These classes are ideally suited to be team taught by instructors from a variety of backgrounds. Teachers from science, technology, graphic arts, technical graphics (drafting), industrial design, graphic design, along with many other disciplines, can play a role in teaching this curriculum.

Currently, there are 12 pilot sites – directed by both science and technology education teachers – in North Carolina teaching the scientific and technical visualisation curriculum. The curriculum development team at NC State University has been working closely with these sites, developing support materials and providing workshops for teachers. In addition, these sites have been critical test beds for instructional materials in development and for developing an initial understanding of how the curriculum is being implemented in real classroom settings.

Visualisation design process

The design process plays a central role in the scientific and technical visualisation curriculum. It is a goal of the curriculum to allow students to experience the design process in a way that mimics its manifestation in real world applications. At the same time, an opaque, understood design process also provides support for the successful solution of a visualisation problem.

The curriculum provides strong support for the dualistic processes in design (Tovey, 1986). On one hand, students are required to have/acquire 'left-brain' knowledge of science/technology concepts central to the systems they are attempting to visualise. At the same time, 'right-brain' knowledge is needed for the holistic synthesis of the graphic visualisations representing the system.

The curriculum also recognises the ill-defined nature of the real-world application of the design process (Cross, 1986b). Students are not provided with rigid rules for the production of visualisations, but instead are instructed in a series of heuristics (i.e. rules of thumb) which must be applied based on the context of the individual problem. Examples of heuristics students are instructed in include:

- when line graphs are more appropriate than bar charts for the display of data
- creating enough contrast between foreground and background colours, based on the viewing conditions of the visualisation

- choosing appropriate points of view of a 3D model scene, based on the dynamic elements in the scene.

Appropriately, as the students work with these heuristics and test them out on specific projects, they begin to refine and develop their own personal set of heuristics for application in visualisation projects.

As convenient as it might be, a rigid design process and overly defined visualisation problems to be solved are unlikely to serve larger instructional goals (Lewis, Petrina and Hill, 1998). At the same time, students need to be explicitly exposed to the design process and provided with some structure, especially earlier in the course sequence. For this reason, a design brief format is used with many of the activities in the courses (Clark and Wiebe, in press). This brief is tailored to the individual assignment and provides key benchmarks which the students are expected to meet. It also provides an explicit set of goals on which evaluation of the project will be based.

Graphics play a central role in the classic industrial design/engineering process (Cross, 1986a; Lakin, 1990; Tang, 1991). However, the visualisation curriculum differs from many other technology and vocational curricula in that the graphics are both the medium used in the on-going design process and the final product. Students have to become aware of the dual role which graphics can play in the course of creating a final visualisation. Whereas if the project is the design of, say, a mechanical device, the graphics created are used primarily as an intermediate communicative medium while working towards a design of the final product. With visualisation design, the graphic is the direct embodiment of the design. The graphic is what evolves and ultimately represents the final product.

For a larger project, the visualisation should go through a number of stages, from rough to finished. Earlier stages will typically involve storyboarding using both hand and computer-based tools. These graphics might typically be confined to communication between the student and his instructor or within the group of students doing the project. The graphics may contain both representations of actual artifacts to be contained in the final visualisation along with other elements. Examples of this second type might be written notes and other graphic elements used to explain processes to create the graphic or shorthand representations of dynamic elements.

As the visualisation project nears completion, the graphics will become more polished and representative of the final visualisations. An increasingly larger percentage of the content of the graphic represents communicative information in a form meant for the final audience. It is important for the students to understand the multiple iterations that a visualisation might go through and the role each iteration plays.

Evaluation

An important part of the visualisation design process is an ongoing process of evaluation. Goal definition at the beginning of the design is the first component of the final design. Students should have a clear idea of what the end goals of the project are. Similarly, visualisation design heuristics used throughout the design process should also be benchmarks used for evaluation. Rather than wait for a single, formal evaluation at the end of the project, visualisations should be evaluated at all stages of its evolution.

The evaluation process is modeled in part on the usability evaluation methods used in industry for evaluating artifacts ranging from consumer appliances to software interfaces (Jordan, Thomas, Weerdmeester and McClelland, 1996). Human factors (ergonomics) principles of interface between technology and humans provide visualisation designers with perceptual and cognitive psychology-based heuristics by which effective visual performance can be evaluated. Similarly, the rhetorical framework used by technical writers also reinforces the human-centric nature of visualisation designs, helping to keep the eventual audience of the visualisations in mind at all times (Mirel, 1998). Finally, practicing professional graphicians have evolved guidelines for both print and electronic media who provide valuable lessons for classroom-based visualisation design.

Given that heuristics rather than hard and fast rules govern much of the visualisation design process, evaluation through a variety of methods should be the norm rather than the exception. Ideally, final review by the end user of the visualisation should take place. The reality of the classroom will not always allow this. Usability evaluation methods also provide for a number of alternative techniques to be used in conjunction with final client review. These methods include checklists based on design heuristics, peer review, and review by usability experts (a.k.a., the teacher).

Technical skill development

Looking at the specific outcomes of this curriculum, students taking this curriculum will have developed competencies in a number of different technology-based areas:

Computer technology

Students use current computer hardware and software to create 2D and 3D visualisations. This creation process requires mastery of a wide variety of computer data input and output devices handling audio, video, static graphic, and alphanumeric-based information. On the computer, this multimedia-intensive process requires an understanding of data storage technologies and management strategies. Movement of information not only happens on single computers, but also across networks. For that reason, the student needs to be able to move information across both local area and wide area networks.

Data manipulation/management

In the creation of visualisations, data is typically transformed from one form to another. These transformations require knowledge and skills on a number of levels. Mathematical skills are often needed to transform numeric data into a more appropriate range of values for visualising, often using spreadsheet tools. Geometric principles are used to spatially organise information on 2D planes and to project 3D objects into the 2D space of printed paper or computer screen. Knowledge of graphic data formats and compression techniques are used to evaluate the best transitional and final formats to hold graphic data in to guarantee the highest quality output in the most efficient amount of digital storage space.

Visualisation design skills

Students need to apply higher order critical thinking skills to the development of appropriate communication solutions. Given a set of computer-based technologies and background in graphic communication principles, students need to define an appropriate visualisation solution appropriate for the time, resources, and target audience.

Communications

Above all else, visualisations are judged on the basis of how effectively they communicate the necessary information to their target audience. Success of this goal is a combination of:

- knowledge and application of the tools used for harvesting and manipulating information and the creation of graphic visualisations
- knowledge and application of visualisation design principles in the context of an appropriate design process.

Scientific visualisation in the classroom

For any educational philosophy to be effective, it must be translated into practice in the classroom. Appropriately, there has been effort to take current thoughts on constructivism and transform them into classroom practice (Appleton, 1993). Not surprisingly, this translation is not always smooth and often involves compromises on the more idealised philosophical elements (Ritchie and Baylor, 1997). Returning to the scientific and technical visualisation curriculum, it is worth looking at how well constructivist principles mesh with this curriculum. Interestingly, based both on how the curriculum is structured and how it is currently being taught at the pilot sites, there is a close of an alignment with a number of constructivist principles.

The pedagogy of a more pragmatic constructivist approach may make use of a number of techniques and ideas. One primary goal is to help students learn how to use the knowledge that they have on hand (Herschbach, 1998). This will involve activities that don't simply require the memorisation of a fixed body of knowledge, but to use knowledge on hand to build a larger knowledge base. Related to this is encouraging a process of enculteration whereby students learn how to use their knowledge in the same manner as a recognised 'master practitioner' (Roth, 1992; Roth, Bowen and McGinn, 1999). This approach recognises that students are serving a cognitive apprenticeship of sorts, learning how to manipulate knowledge to ways deemed appropriate and productive by teachers, more knowledgeable peers, or professional practitioners. This conception of the dynamic use of knowledge stretches canonical knowledge into the realm of canonical practice.

This more pragmatic constructivist approach emphasises many elements that are strengths in the scientific and technical visualisation classroom. Of particular interest are the following three areas:

1. the movement from well-structured to ill-structured problems
2. the role of group activity
3. the importance of ongoing evaluation and reflection.

Through the course of the year, the teacher cycles between presenter of canonical knowledge and facilitator of its application through each module. In addition, there is the larger cycle of moving from more to less presentation of knowledge to facilitating the students' acquisition of it. Also overarching this larger cycle is the integration of more and more elements of the design process. Whereas the more discrete projects earlier in the year do not require much problem definition or

solution refinement, projects later in the year engage a fuller design process. Students move from solving the problems presented by the teacher to posing their own visualisation problems to be solved. Moving from problem solving to problem posing challenges students to make use of higher order thinking skills that requires acquisition and synthesis of new knowledge within their framework (Herschbach, 1998; Lewis *et al*, 1998).

Even as the movement is made from more to less structured activities, there is still the goal of providing guidance to the information seeking behaviour (Appleton, 1993). In the visualisation curriculum, the information seeking may be both in the realm of the science/technology topic which the visualisation is about, visualisation techniques, or use of specific computer-based tools to execute the visualisation. In the visualisation curriculum, this guidance can be provided in a variety of social groupings. In some cases, specific knowledge can be transmitted by the teacher to the class as a whole. In many situations, activities are left more ill-structured. Where appropriate, groups of students may come together to work on acquiring and testing the knowledge needed to come up with a solution. This is likely to be a combination of cooperative and collaborative work. For example, they may cooperatively try and come to an understanding of the science/technology concepts underlying the visualisation they are to create. When it is time to produce the time-consuming visualisations, they divide the graphics generation tasks among individuals. Whenever appropriate the teacher-as-facilitator can join groups to answer questions and evaluate progress.

Ongoing evaluation becomes a critical component of the visualisation activities. Evaluation has to take place on a number of levels. First there has to be some assessment as to whether the student has successfully grasped the underlying science/technology concept that the visualisation is about. Here it is usually possible to identify benchmark, canonical knowledge by which to base evaluation on. There is still the problem of how to effectively probe the student about their knowledge. Here, the graphic output – produced as either early artifacts in the design process or later, more final pieces – becomes a powerful communication medium (Gordin, Edelson and Gomez, 1996). The product becomes a point of reflection of personal constructions of knowledge (Blunden, 1997). These graphics can be used for individual reflection, as part of a group negotiation of knowledge, or in discourse with the teacher. In all cases, the requirement of committing ideas to a graphic becomes a unique hallmark of this curriculum. Whereas many other courses of study may use verbal or written communication for this knowledge representation, this curriculum uses graphics as its primary, though not exclusive, form.

There also has to be an evaluation of the application of visualisation principles. These principles, like most principles of design, are better understood as heuristics rather than hard and fast rules. As such, successful application of these heuristics needs to be evaluated within the context of a design problem. For that reason, prior identification of goals for the visualisation is critical. Part of those goals is the identification of the final audience (context of use) for the visualisation. As much as possible, this audience should be used to help evaluate the visualisations (Liu, 1998). This means that in addition to having earlier iterations of a visualisation critiqued by peers and the instructor, more finalised versions might also be critiqued by individuals outside of the classroom. Using outsiders, including working professionals in the scientific/technical field in which the visualisation is based, also helps support authentic practice. Here too students are required to understand the means of communicating in this particular field.

Finally, students need to be evaluated on how well they were able to apply the tools used to create the visualisations. In principle, mastery of the underlying technology should be evident in the final product (Lewis *et al*, 1998). In the visualisation curriculum, success or failure is unlikely to be a binary proposition. Earlier activities may focus more on applying these tools in a discrete fashion, making it easier for the student to reflect on the outcome and judge for themselves as to the success of mastery. Students should be able to make use of multiple resources (e.g. knowledgeable peers, tutorials, and the teacher) for developing understanding of the capabilities and appropriate application of these tools. In later assignments, evaluation of understanding and use of these tools will be based more on a measure against the goals of the project, and the judgement of the intended audience as to its success.

Example activity

Simple machines is a topic/unit that is often covered in the principles of technology curriculum in North Carolina (CORD, 1990). As a topic area, it serves a number of important goals: it provides an introduction to Newtonian physics, it involves key building blocks to more advanced mechanical technologies, and it is readily adaptable to lab-based activities. It is also a very appropriate

activity for the scientific and technical visualisation curriculum, taking on a different tack.

Problem definition

The instructor provides an introduction to simple machines, giving the students an opportunity to explore the principle of transforming energy into work and the concept of mechanical advantage. Differing types of simple machines (e.g. screws, inclines and pulleys) are discussed and demonstrated. From this the problem is set forth: visualisations need to be created so that each student group would be able to stand up in front a class of peers (maybe a principles of technology class) and explain the principles behind one of the simple machines. The final output would be a PowerPoint presentation and should contain both static and dynamic graphics.

With this introduction to the problem, the instructor has laid out the scientific/technical topic to be visualised. In addition, they have also set some basic constraints concerning the types of visualisation methods to use. Finally, a target audience and delivery method has been defined.

Information sources

With any visualisation, information has to be gathered. This information usually takes two primary forms: background information on the scientific or technical topic to be visualised and data associated with the actual system being investigated. Though the instructor may have laid out some of the basic concepts of simple machines, it is expected that the students will have to do more investigation to provide enough materials to create a visualisation from. This background work will both be on simple machines in general and the specific machine chosen for the project, for example, pulleys.

In the case of creating a visualisation on pulleys, key variables need to be identified. These variables will both define the system, organise data that might be collected or generated. In the case of pulleys, key variables might include the type of pulley (simple or compound) and how energy and work are defined (Figure 1). For example, force on the string that the person pulls and the force on the pulley from the hanging object. The length of string pulled out, how far up the object moves, and over what period of time may also be defined.

Data on these variables can be collected a number of different ways. One way would be to empirically generate data by running actual experiments (Figure 2). Records of these experiments can be made holistically through video and by recording values numerically at set intervals. Data can also be generated theoretically by using the appropriate mathematical equations using a calculator, a spreadsheet, or other appropriate computer-based tool. Of course, theoretically and empirically derived values can also be compared to each other.

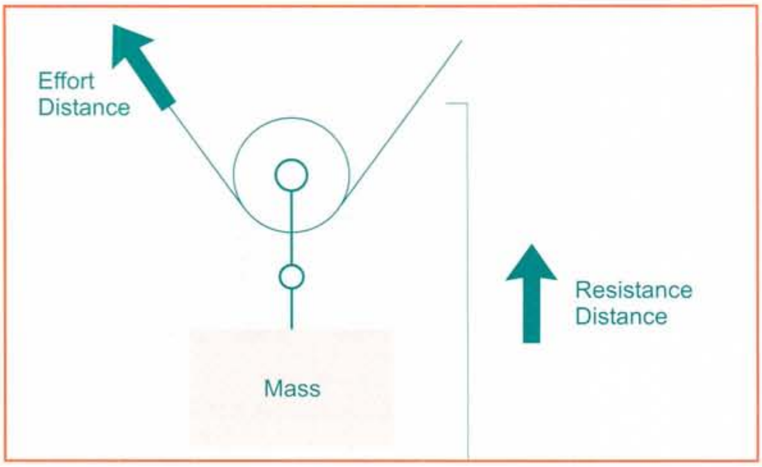


Figure 1: Schematic of a pulley system. This visualisation can be used: to help the student understand the principles of pulley systems, organise other visualisations and be part of a final presentation.

Visualisation methods

Students gather and synthesize information on simple machine systems to gain an understanding of the system well enough to visualise it. Decisions are made as to how best to convey selected information about the system to the target audience. Already two possible visualisation methods have been shown: static schematics of the pulley system and archival video footage of an actual experiment run with the pulley. There are many other possibilities for visualisation techniques. Identification of key system variables and the collection of empirical data may lead the students to create graphs of their data. Combined with knowledge of the final delivery medium and graphic design heuristics, appropriate graphs could be created (Figure 3).

Final synthesis

A final synthesis of the visualisations is produced near the end of the project period. Here the individual visualisations need to be brought together into the medium for presentation (i.e. PowerPoint). Together with the visualisations there will be supporting text

Figure 2: Video of a pulley system. This is a still from a digital video clip of a pulley system in operation.

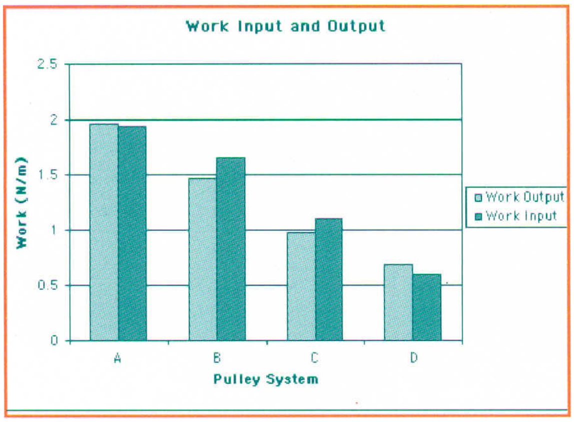


Figure 3: Graphed data from the pulley system. This graph represents empirical data collected from an experiment with the pulley system.

and secondary graphic elements used to enhance the visualisations (Figure 4). Decisions concerning the final presentation include: whether the audience will use the material in a self-paced environment or presented to them, how much time should be allotted for the presentation of material, and what computer hardware/software will be available for presentation. The final presentation by the student provides an opportunity to gain valuable feedback concerning the effectiveness of their visualisations, along with gaining experience in public presentations.

Looking specifically at the previously outlined example of the simple machines activity provides a point of context. As an activity, it falls somewhere in the middle of the pedagogical continuum of problem complexity. It is a problem defined by the teacher (i.e. design a series of visualisations depicting the principles of a simple machine), but the exact output of what constitutes the visualisations is not. The teacher may specify that certain techniques be used without specifying exactly how the results are defined and synthesized. It would be assumed that there would be some level of mastery of specific computer graphic technologies and some understanding of communication principles. At the same time, this activity may be an early opportunity for the student to bring together a number of different visualisation techniques into a single presentation.

Conclusions

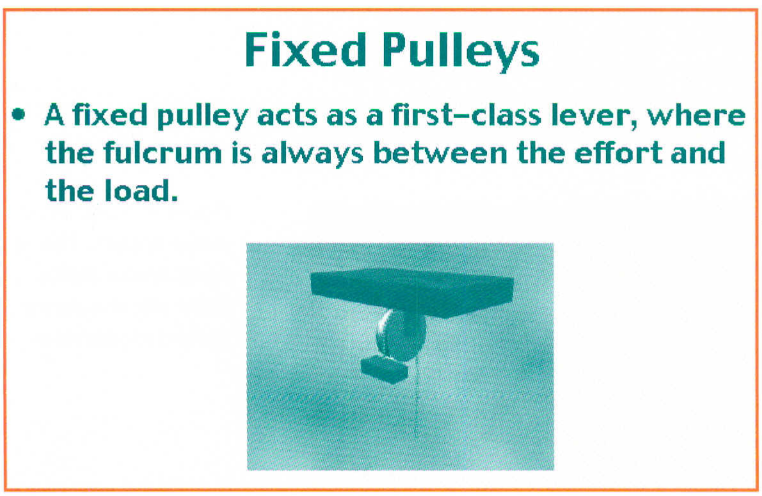
The scientific visualisation curriculum takes the tools and techniques used by scientists, engineers and technologists into the technology education classroom, using the design process as a vehicle for exploring topics in science and technology. Unlike many other technology-related curricula, science and technology play a central role both in the creation of the end product, but also the subject matter itself. Within the structure of the visualisation design process, students are allowed to explore in-depth science and technology topics while they learn about the effective application of information and computer technologies to communicate their ideas.

This curriculum supports the development not only of valuable information and computer technology skills, but also higher order critical thinking skills necessary to apply these tools. By scaffolding through well to more ill-defined visualisation design problems, students learn how to effectively apply graphic communication principles and computer graphics tools to effectively communicate their ideas. By virtue of its integration with science education, there is the added benefit of students being able to revisit science concepts in the new and motivating context of creating visualistions which communicate the core scientific concepts. Group activity designed into the curriculum provides opportunities for students to construct scientific knowledge in a collaborative setting. In groups ranging from one-on-one to the whole class, these collaborative settings also provide valuable feedback as to the effectiveness of their visualisations. A design brief format provides a structure in which the students can both receive and provide constructive criticism of the visualisations.

Future plans for this curriculum include developing a clear articulation between the curriculum and emerging national and international standards in technology and science education (c.f., ITEA, 2000; NAS, 1995). This articulation will help further the goal of disseminating the benefits of:

1. the use of graphics as a scientific and technical communication medium
2. the use of the design process in technology education

Figure 4: Pulley system slide. Text and graphics integrated in a slide from a final presentation of pulley system principles.



3. the integration of science and technology education.

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