

# **Footprints to function sense and a sense for the geometry of three- dimensional space**

(Laying a firm foundation for function analysis and the method of coordinates)

**Sandra Scholtz**

School of Teacher Training  
Faculty of Education  
University of Pretoria  
Tel.: (012) 4205550  
[s.scholtz@gk.up.ac.za](mailto:s.scholtz@gk.up.ac.za)

**Jaco Scholtz**

Independent Software Architect

## **Abstract**

*The vitality of mathematics, as mathematicians experience it, is in sharp contrast to its public image of being boring and complicated.*

*Today, we live in a technological society where there is hardly any aspect of life in which mathematics does not play a significant (though often hidden) part.*

*Mathematical literacy for efficient functioning in a technological society can no longer be the goal of an elite subset of the school population. Every student must be equipped with a combination of personal skills, technological skills, and thinking skills in order to apply mathematics meaningfully. These are the prerequisites for understanding the world in which we live, for realising the potential of technology.*

*Attracting students into mathematics seems especially important in the early teens before they might stop taking the subject, leaving no future chance to discover parts of it that might appeal to them and cutting themselves off from opportunities to pursue studies that depend on higher mathematics.*

*Everyone has the ability to acquire sufficient mathematical skills if he or she has the desire to do so. The key is first to arouse learners' interest and enthusiasm and then let them discover by exploring and experiencing what mathematics is really about.*

*The challenge is to reform and recreate personal attitude in an innovative way, based on:*

- *A hands-on, creative, playful approach*
- *Carefully selected activities*

- *Open-ended problems*
- *The use of natural curiosity*
- *Encouragement of a sense of mathematical ability (can-do attitude)*
- *Scaffolding – allowing students to perform tasks that would normally be slightly beyond their ability without the assistance of a teacher.*

*Thus a cognitive schema is unwittingly established for the later development of more advanced mathematics. The research on which this paper reports can be seen as the second spiral following the previous action research:*

*GRAPHING COMPUTER SOFTWARE: UNLOCKING FUNCTION SENSE FOR ALL*

*by Sandra Scholtz and Hanlie Botha and reported on during the Third International Conference on Science, Mathematics and Technology Education, January 15-18, 2003, East London, S.A. (Curtin University of Technology, Australia and East London Campus, Rhodes University, South Africa). The paper is included in the conference proceedings and will be published during 2003.*

*The results of the first spiral offer a prioritised list of criteria for success in designing a new mathematics practical course that improves the degree to which the needs of the relevant students are addressed.*

*In the second spiral the abovementioned list of criteria is further developed, again prioritised and used to arrive at an integrated computer-assisted programme for developing function sense and a sense of the geometry of three-dimensional space. The program is hands-on, creative, computer aided and interactive. The design aims to provide accessibility and mathematical empowerment to all.*

*When completed, this programme will be distributed on CD at an affordable price for the use of public schools, private schools, home schools and individuals.*

*The design makes the program fun, playful, accessible, portable and inexpensive and gives learners a chance to play the game and acquire the concepts – not only learn the rules.*

## **Introduction**

*“Scientific education is seen as the gateway to future economic prosperity, the driving force behind scientific and technological advancement, the means to combat unemployment, the *sine qua non* for the effective defense of a nation and the spearhead of social progress and equality” (Pouris, 1989).*

*Despite this multitude of benefits and the continuous scientific and technological intensification of the world we live in, scientific and technological education in South Africa does not deliver a large enough talent pool with a good background in mathematics and physical science and a preference to study science and engineering on a tertiary level. The following table shows*

the comparison of the number of engineers serving the population in a few different countries:

COUNTRY	POPULATION	NUMBER OF ENGINEERS (% of population)
CANADA	30 337 000	169 512 (0.56%)
UK	58 821 000	265 000 (0.45%)
GERMANY	82 072 000	150 000 (0.18%)
AUSTRALIA	18 439 000	100 000 (0.54%)
SA	42 209 000	14 730 ( <b>0.035</b> )

Source: Unesco, 2003

Ironically, the engineers and scientists trained in South Africa are of such high quality that it is a well known fact that they are actively recruited on a continuous basis by most first world countries, depleting the number still further.

The science education system must provide technologically literate citizens as well as produce new generations of professional scientists, engineers, and technologists. The latter task is dependent on the first; as a technologically illiterate population will not only be indifferent to scientific and technological needs of society, but will also tenuously resist the existence of what seems an incomprehensible powerful elite. The difficulty in achieving scientific literacy is that efforts in this area are long-term and diffused.

In spite of that, there has been much progress in South Africa in recent years to promote a culture of mathematics and science by government bodies as well as the private sector. Examples are the following:

- **Sasol SciFest** – The National Festival of Science, Engineering and Technology is a project of the Grahamstown Foundation sponsored by Sasol Limited. It was launched in 1997 and was the first of its kind in Africa. Each year the organisers produce a fascinating programme that aims to break through popular misconceptions and to create a new mindset about science, engineering and technology. Scientists are given the opportunity to make science accessible to ordinary people and show that science, engineering and technology underpin business and everyday activities.
- **FEST-** The Foundation for Education, Science and Technology. It is one of the groups of the National Research Foundation (NRF) and takes responsibility for developing people in South Africa in the fields of the natural and applied sciences, engineering and technology. The NRF developed out of the FRD – The Foundation for Research Development that was established as part of the CSIR in 1984 and

became an independent science council in 1990. Its activities include science and mathematics olympiads, science outreach funding for expo's, seminars, exhibitions, workshops and a Museum of Science and Technology with SciQuest, a travelling science-educational exhibition aiming to promote science, engineering and technology especially in underprivileged communities. FEST also manages a national programme on Public Understanding of Biotechnology.

- **The Science Edutainment Centre** in the Newtown Cultural Precinct in Johannesburg has interactive exhibits aimed at promoting science. The total cost of this Gauteng Education Department project currently amounts to about R150-million and it is expected to attract approximately 300 000 learners and 90 000 members of the public per year.
- **Centres** such as MTN and TELKOM Centre in Canal Walk and the Waterfront in Cape Town.

The above activities have promoted - and still hope to further promote - the enthusiasm and interest in science, engineering and technology necessary for students to want to follow career paths in these fields. What is also needed, though, is a sound tertiary education that is only accessible for learners in the academic track taking the most demanding courses in science and mathematics.

A recent discussion on TV1's actuality show 'Asikhulume / Lets Talk' on the topic: 'Is our education system equipped to produce enough world class scientists?' (SABC TV1, viewed 27 June 2003) with special guest Mosibudi Mangena, the Deputy Minister of Education, also included other guests, such as Dr. Sibusiso Sibisi, the president of the CSIR, Dr Dwight Triegaart of Africon, and Karl Lubout, Marketing Manager of Rand Water Quality. They agreed that, in spite of all the positive inputs such as those mentioned above and the immense interest it promotes amongst the youth, the mathematics and science achievement of the majority of our schools compare very badly with other countries – even with those on the African continent.

In a graph on the Mathematics Achievement Scale Score shown on the programme South Africa rates last after, in ranking, Singapore, Hong Kong, Canada, Australia, The United states, England and The Islamic Republic. It is also the case for the Science Achievement Scale Score. The following countries, in ranking, was shown to be above South Africa: Chinese Tai Pei, Australia, England, Canada, Hong Kong, The United states and the Islamic Republic.

According to the Deputy Minister of Education, Mosibudi Mangena, even other countries in Southern Africa, like Tanzania, Swaziland and Botswana do much better, although we spend more per capita on scientific education than those countries.

In the words of the presenter, Xolani Gwala: "Where do we lose it? How does the department hope to turn things around?"

Although there are multiple reasons, the panel agreed that the quality and quantity of teachers in science and mathematics are decisive factors in determining the size and quality of the science and engineering talent pool. We need teachers who are passionate, understand the work and can convey the message. However, in South Africa, in spite of efforts to train and retrain teachers, almost 50% of mathematics and science teachers are still unqualified or under qualified. Deputy Minister Mangena stressed that there already are positive results, especially from The National Strategy for Mathematics, Science and Technology Education project, targeting 102 schools. Lack of funding is, however, a fact of life and although they work as hard as they can and do experience improvement all the time, it is slow.

Other reasons mentioned were the lack of facilities, especially in township schools and schools in the rural areas, lack of teaching aids, problems with language, the lack of role models as science and engineering are still far removed from township children, and schools forcing learners to take mathematics on standard grade to ensure a higher grade 12 pass rate.

Something not mentioned by the panel, however, is the degree of difficulty of these fields of study and the discipline required to master them (Feynman, 1998; Devlin, 2000). Large bodies of knowledge are required to cement understanding and create the ability to work in scientific fields. It often requires a level of dedication beyond what is considered “normal” for most people. Creating something new in science is a problem of extreme difficulty, as scientists are not free to act as they please. All new ideas must be consistent with the knowledge of the way nature really is. This is only possible if a large store of relevant knowledge has been accumulated to draw upon, which can only be achieved through long-term focus. Add to this the degree of abstraction of the work and the degree of rigor required in carrying out the reasoning processes (Devlin, 2000) and it becomes clearer why only a small minority of people are prepared to undergo this process, to make sacrifices and not place greater value on social interactions, social skills and sport as most people do.

## **Background**

At the School of Teacher Training of the University of Pretoria we are fortunate to have the use of the Master Grapher for Windows program with supporting study material developed for students pursuing a scientific career. In spite of the fact that the excellent quality of the program has been verified by experience and research (Steyn, 1998), we nevertheless became aware that a significant percentage of the student teachers undertaking academic mathematics courses on the Groenkloof Campus have a negative attitude towards the mathematics practicals.

Most of the students taking academic mathematics on the Groenkloof Campus do not, because of insufficient school results, qualify for admission to the regular mathematics courses on the main campus, nor do they wish to do so. Their focus is on a teaching career, and not a career in technology.

Given the influence of their experience in the mathematics practicals on the way that they will think about and approach their own teaching in mathematics, the necessity to adapt the practical course to a more acceptable format to suit the needs of our particular students became clear.

In order to bring this about we undertook a qualitative action research study to explore the students' experiences, focusing on their attitudes.

The research findings indicated that the students were in principle generally positive about the mathematics practicals, but experienced a number of significant frustrations that are described in the following themes that emerged from the data analysis:

- Insufficient background knowledge
- The need for real-world context
- The need for more creativity
- Applicability in the classroom
- Cost
- Time pressure
- The need for group work
- Venue (availability)

The above themes served as basis for the establishment of criteria for success in the design of a new mathematical practical that more appropriately addresses the needs of the particular students.

Optimal design effectiveness and efficiency, given the specific circumstances, was achieved by prioritizing the criteria.

## **Rationale**

One of the planned future outcomes of the study described above, was an integrated computer-assisted interactive programme for the development of graphing sense that can be distributed at an affordable price on CD for the use public schools, private schools, home schools and individuals.

In the quest to design such a programme that can help learners gain confidence in their ability to solve science and technology related problems and, in doing so, develop a deeper conceptual understanding of the mathematics involved, the design criteria of the previous action research study were carefully examined and found to be inadequate for the purpose.

From experience, it is known that some people with an interest in science, engineering and technology are nevertheless unable to succeed in the field, while others are able to excel. It was therefore decided to follow a pro-active path and to explore possible environmental factors that contributed to launch successful people into their careers. These factors could then be used to further develop the design criteria mentioned above in order to enhance the quality of the programme.

## **Aims**

The aim of this study was to explore the environmental factors that stimulate learners to become involved in the sciences and pursue successful career paths in scientific and technological fields, in order that the findings could be applied to design affordable interactive material to enhance the teaching and learning of mathematics.

To achieve this aim, the critical question asked was: “What are the perceptions of successful workers in scientific or technological fields of the external influences that shaped their attitudes and made it possible for them to be launched into their careers?”

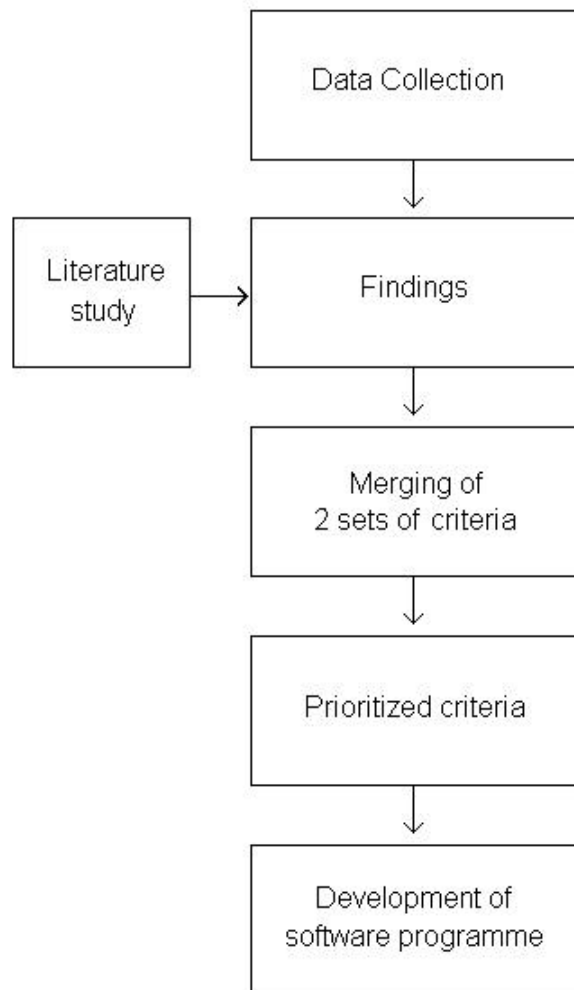
The methodological invention of this research was to devise an innovative methodology for the development of study material that focuses on prioritized qualitative criteria for success before the design of a product commences, ensuring better quality and cost effectiveness.

## **Context**

This study did not investigate biological or genetic influences that are present at birth, but only explored environmental factors that may encourage more learners into scientific and technological fields.

The data collection was limited to people who were successfully trained and are successfully working in a scientific or a technological field.

## Research strategy



## Limitations of the research

The biggest limitation encountered was the acute shortage of time due to the extensive workloads of both the researchers. The methodology is of such a nature, however, that the criteria for success can always be updated at any later stage.

## Data collection

As this study focuses on the perceptions of individuals who have successful careers in a scientific or a technological field of the influences during their earlier experiences that could account for their present success, it can be described as a retrospective longitudinal study. At the same time, however, it builds on the action research described above, and in that sense it is the second spiral, or further development of, that action research.

- The initial data was collected from an in-depth retrospective analysis of the childhood- and later experiences of one of the researchers currently working as a software architect (referred to as Initial Data).
- Semi-structured, individual, interviews were then conducted with three engineers and two statistics graduates employed by the CSIR. A very talented black lady civil engineer and the two statistics graduates coming from a township background added the needed diversity (referred to as Interview A1; A2; A3; A4; and A5).

The above data was analyzed to identify prominent themes of factors that contributed to the attitude and dedication that made it possible for these people to successfully work in scientific or technological fields.

The findings of the above information were then compared to the findings of the original action research to determine criteria for success that could be used in the design of the intended programme.

These criteria were prioritized with the aid of a decision support system designed for qualitative decision-making in order to ensure optimal results under the specific circumstances (Scholtz, 1992).

The criteria for success were measured against the design principles for a Constructivist learning environment as synthesized and summarized in a Constructivist Checklist on her website by Elizabeth Murphy (Murphy, 1996) to determine whether they are in line with the characteristics of Constructivist learning and teaching.

The findings of the research thus reported were then also compared to the findings of a literature study.

## **Validation**

Triangulation, peer examination, independent coding and comparison of information at different stages of the research ensured credibility. The latter was also used in the interviews to control consistency.

The unique circumstances and relationship of the researchers in this study, not only as mother and son, but also mathematics teacher and learner, as well as computer- and electronics –club organizer and club member, greatly contributed to the verification of the information. Shared experiences over a number of years with the large number of club members who later pursued careers in science and technology also added to the ability of the two researchers to recognize and evaluate key incidents.

## **Research findings**

The instrument that yielded the best information was the in-depth retrospective analysis of the childhood- and later experiences of the one researcher working as a software architect. Findings from all the interviews,

though, expressed remarkable similar perceptions. A key observation about the data was that all the themes that emerged can in one way or another be seen as factors contributing to the building of self esteem, or a 'can do' attitude, as well as the joy that evolved because of it. In the words of one of the interviewees: "A general belief that I am good enough to attain great things" (Interview A1). He went on to add that this was the most modest way to phrase it, but that he is convinced that you have to believe that you are destined to achieve great things in order to accomplish them.

This might be the key to the elusive motivation that drives some people to develop the knowledge, talent and skill that empower them to achieve in these difficult fields, while others find it too exhaustive.

The reporting on the main findings of the research is dealt with under each of the following common themes that emerged from the data analysis:

### ***The need to start young***

All the interviewees stressed the importance of early exposure to how science really works. There were, however, two interpretations of what was regarded as young - on the one hand pre-school and early primary school and on the other early high school.

In one case the intensity and enjoyment in describing activities during childhood that in one way or another produced something that could do something, be it a Lego construction with battery driven gears or making a toy tractor or a rocket from wire and pieces of scrap metal (Initial data), was very obvious. It was also thought to be these activities that caused him to look at things in an analytical way.

Recalling the fascination with computers from the first time they encountered one, as well as the passion with which it was told, was very similar for those who were lucky enough to have had the experience.

"My father showed me at a very early age how to write simple programs and how to compile and run them. It did what I told it to do. That thrilled me and gave me a real sense of accomplishment"(Initial data).

### ***Personal involvement by someone who clearly conveys the message that he or she believes the child can accomplish certain goals***

Every one of the interviewees mentioned the importance of role models. The prominent role played by fathers was quite significant. It was clear that the personal involvement of the role models was very important because of the affirmation it provided. The trust showed by the role models somehow instilled feelings of competence and self esteem.

"The proud look on my dad's face when the bridge was inaugurated told me that he was right all along when he said that I have what it takes to be a civil engineer one day" (Interview A2).

“The event that made me believe that mathematics can be figured out if you try long enough, were some graphs my father gave me to plot at about 7 years of age. I felt awfully clever and decided that I could do this stuff” (Initial data).

“A highly respected electronics engineer took the trouble to explain to me what they were doing on a very important project. It fascinated me”(Initial date).

“My father was an engineer – I had early exposure to quantitative and analytical thinking and I accompanied him on excursions from time to time – it interested me - the role model thing” (Interview A3).

### ***Coming from a home where intellectual achievements and exacting standards are highly valued***

A significant number of those interviewed had received an unusual amount of intellectual stimulation at home. This could also come from friends, as mentioned by one of the engineers. Interesting quotations were the following:

“Parents and grandparents encouraged an inquisitive mind. I had lots of books available to read on all different subjects and had discussions on ‘mature’ science topics from an early age” (Interview A1).

“You were just lucky if you were brought up this way” (Initial data).

### ***Involvement in projects that are intellectually challenging***

Although puzzle solving and relevant shows and films were mentioned, the projects that were intellectually challenging were, by most, felt to be far more significant. This was also mentioned as one of the main inciters to the gathering of further knowledge.

Olympiad projects were also very important and recalled with great joy by three of the interviewees.

“Maths and Science Olympiads – I got to taste the joy of figuring something difficult or new out” (Interview A3).

Special mention of a course in electronics at a technical college during early high school was made by one of the interviewees as a very significant occurrence that greatly contributed to his ability to pass the very difficult first year engineering course (Initial data).

### ***Access to resources***

Libraries were mentioned, but nearly all the interviewees mentioned books – also books on other topics – that were in the home or specially bought for them. Access to computers was seen as most significant.

### ***Intrinsic interest – finding science and mathematics enjoyable and significant***

End users of computer-designed technology seldom have an idea of the mathematics involved in the processes. They only notice the effects in the form of increasingly easy-to-use software applications and operating systems, as well as in more flexible services being provided by such industries as banking and telecommunications. Once the paradigm shift has been made, though, it seems to have a momentum of its own.

“I think that my interest in the special effects created in films triggered my interest to write computer games. It must have all started with the fun we had with cartoons and my dad explaining how it worked” (Initial data).

Interestingly, both the statistics graduates pointed to their enjoyment and success in mathematics as their main influence.

“I enjoyed and excelled in mathematics and science compared to other subjects”(Interview A4).

“I could spend hours doing my tutorials and the more I spent doing my work the more I became happy and content with life” (Interview A5).

### ***The interactive quality of the factors***

Most of the influences reported also entailed activity of some kind.

### **Determining the criteria for success from the above mentioned themes and the results of the action research**

*The need to start young* does not overlap with any of the criteria in the action research study, and will therefore be taken as a criterion on its own. ‘Young’ is taken to be late primary school / early high school.

*Personal involvement by someone (a role model) who clearly conveys the message that he or she believes that the child can accomplish certain goals* can of course not be accommodated as such, but the self esteem built in this way can, at least in part, be substituted by providing a controlled progression of small successes building confidence and self esteem as the user masters the increasing complexity. This overlaps with ‘scaffolding’ from the previous set of criteria, which allows for the learner to perform tasks that would normally be slightly beyond their ability without the assistance of a teacher. This criterion will be named *scaffolding*.

*Coming from a home where intellectual achievement and exacting standards are highly valued* cannot be provided by a learning- or teaching aid, but will hopefully play a role in future homes. It will not be considered as a criterion.

*Involvement in projects that are intellectually challenging* stresses the need for carefully designed projects that can stretch the ability of the users to a sufficient level to build real self esteem.

*Access to resources* will be grouped with cost, venue and time-pressure in the criteria in the action research study, and named AVAILIBILITY.

*Intrinsic interest* will be grouped with real-world context, creativity, the need for group work (synergy) and usefulness (as a teaching aid) and named as such.

*Interactive involvement* is clearly a criterion in its own right.

### **Prioritising the criteria**

Each of the researchers evaluated every criterion against each of the other criteria on a trade-off basis making use of a qualitative decision support system for the use of individuals or groups. The consensus values were discussed and the results, in decreasing order of priority, are reflected in the following list:

Availability – the best material is of no use if it is not available (cheap)  
Interactive Involvement  
Scaffolding  
Intellectually Challenging  
Intrinsic Interest  
The Need To Start Young

These criteria were found to be in line with the characteristics of Constructivist learning as summarized in a Constructivist Checklist on her website by Elizabeth Murphy (Murphy, 1996).

### **Literature study**

Firstly, a few very eloquent illustrative quotes are given to emphasize the relevance of this research:

"Barbie was right: maths is hard. Anyone who tries to claim otherwise doesn't understand what mathematics is." Devlin (2000) expands on this well-known fact, but not as eloquently as the difficulty of Physics is described in the introduction to *Six easy Pieces, the fundamentals of physics explained* (Feynman, 1998):

"...all physics is rooted in the notion of law – the existence of an ordered universe that can be understood by the application of rational reasoning. However, the laws of physics are not transparent to us in our direct observations of nature. They are frustratingly hidden, subtly encoded in the phenomena we study. The arcane procedures of the physicist – a mixture of carefully designed experimentation and mathematical theorizing – are needed to unveil the underlying law like reality."

Richard Feynman has become an icon for late twentieth-century physics – the first American to achieve this status. He attributed the launching of his remarkable career to the way his father taught him to notice things and explained to him the underlying principles. His father's contempt with the memorising of bird names is a good example:

“You can know the name of that bird in all the languages of the world, but when you're finished, you'll know absolutely nothing whatever about the bird. You'll only know about humans in different places, and what they call the bird. So let's look at the bird and see what it's *doing* - that's what counts.”

It taught him the difference between knowing the *name of something* and *knowing something* at a very early age.

“Not having experience with many fathers, I didn't realize how remarkable he was. How did he learn the deep principles of science and the love of it, what's behind it, and why it's worth doing? I never really asked him, because I just assumed that those were the things fathers knew” (Feynman as told to Leighton, 1992).

Steve Wosniak, who together with Steve Jobs designed and marketed the Apple Computer, grew up in a kind of 'typical Silicon Valley neighborhood' where a lot of 'electronics kids' were running around, and all their projects were in electronics. He also credits his father who helped him learn things that weren't taught at school as well as helped him with his electronics projects.

About the diodes and transistors given to him to be used in science fair projects, he said:

“There is a certain window in your life when you're very young and you get a few of these things in your hands. And then, for the rest of your life, they're familiar and they're friends and that's your thing.”

About science fairs: “Winning science fairs at an early age or even entering science fairs was also important. If you enter a science fair and do something well, you get a lot of positive feedback from parents and teachers and the like. In your head, being an inventor becomes a good thing” (Ochse, 1994).

Other findings from the literature study supporting the findings:

- A lot of pleas are made for a more creative, enjoyable, playful approach to the learning and teaching of mathematics (Hoyles, 2001; Flannery, 2000; Sinclair, 2001).
- The need for programmes to be accessible, portable, and inexpensive is pointed out (Boughlaghem, Wilson, Beacham et al, 2002).
- The applicability of technology as a tool in teaching students how to learn is shown by Churach and Fisher (Churach and Fisher, 2001).
- It is important that the environment must be psychologically stimulating in order to capture learners' interest (Polaki and Nenty, 2001).

- Studies indicated the potential of elevating mathematical thinking in a technology-enriched environment by providing good motivation and opportunities to work in an open-ended way (Mok et al., 2000).
- Teachers of mathematics should be aware of and accommodate diversity in instructional activities (Maree and Steyn, 2001).

## Conclusion

The best teaching can only be done when there is a direct individual relationship between a student and a good teacher – a situation in which the student discusses the ideas, thinks about the things, and talks about the things. In our situation in South Africa we have so many students to teach that we have to try to find some substitute for the ideal. We hope that the software that is in the process of being developed will make a contribution.

The software will not try to cover a particular curriculum, or part thereof, but will place emphasis on exploring underlying mathematical concepts. It will be designed to lead the user through a series of specially designed sequential challenging activities in such a way that someone with little or no previous experience in the given topic will be able to solve a complex problem. Every track will end with an open-ended tool that the user can ‘play’ with and apply to own challenges in order to develop competency and the feeling of accomplishment necessary to build self- esteem.

Every project will also have associated documentation for teachers or parents explaining the relevance to mathematics and a list of activities that can be used at earlier stages to establish a foundation from which further progress is facilitated.

It is hoped for that, in time, other tracks will be added on to the first one.

“Achieve the (seemingly) impossible:

Consider the launching pad in life offered by science and mathematics and step forward to them as the most powerful springboards to launch you into the future and the realization of all you wish for yourself” (Mark Shuttleworth).

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