Computers as Cognitive Tools in Architecture Education

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Abstract

In a problem-based, computer-intensive learning environment, what is the nature of the interaction between student characteristics, computers and cognition? The question is examined in the context of an intensive study of 19 students of Architecture undertaking a six month problem-based course in which they were required to work collaboratively on the design and construction of interactive 3D models using a range of software in a Silicon Graphics laboratory. The research method was predominantly naturalistic and data-driven, employing video observation, interviewing, mind mapping and mental modelling. The computer tool used to organise, search and report on the data was NUD•IST (Non-numeric Unstructured Data – Indexing, Searching & Theorizing). The research strongly supported the constructivist paradigm of learning and isolated a range of factors which are relevant to successful cognitive construction in computer-rich environments: approach to learning, as measured on the Study Process Questionnaire; declarative, procedural and contextual knowledge of computing; the ability to make connections between computing and domain concepts; metacognitive awareness, in particular the conscious use of distributed cognitions; and recognition of the 'affordances' of the computer system. The highest achieving students exhibited an overall deep approach to learning (with above average scores on deep motive) and a high level of contextual computing knowledge and structural integration of domain and computing concepts.

Context

In common with many schools of Architecture, the University of Hong Kong provides a three-year undergraduate program (Bachelor of Science in Architecture) followed by a two year professional degree (Master of Architecture). The two are normally separated by a year of work experience in a commercial architectural firm.

Unlike university disciplines which are based on a body of written text and can be taught by lectures and tutorials, architecture is multi-disciplinary and performance-oriented. Designing imaginative but viable structures demands that students can comprehend and manipulate abstract concepts, processes, visual images and physical objects, which means that teaching and learning rely heavily on 2D images, 3D models and moving pictures. In addition, the nature of design problems requires students to develop heuristic reasoning processes based on gradually acquired sets of rules, inferences and strategies. In recent times the traditionally generalist nature of the architectural curriculum has come under pressure as the scope and extent of the separate disciplines of structures, services, construction materials, architectural history and environmental studies have expanded exponentially in scale and complexity. Added to this has been the revolutionary impact of computing on all aspects of the architecture discipline.

The Action Learning Project aimed to develop a teaching strategy which responds to these changing conditions while exploring and testing the potential of high-end workstations as an interactive teaching medium. The teaching staff involved see it as the precursor of a major change in professional educational methodology for architecture education (Bradford, 1995; Bradford, Ng and Will, 1992; Hart, 1996a; Will, Bradford and Ng, 1992; Will, Bradford and Ng, 1993).

Building Systems

Building Systems is offered as an elective unit in the first year of the Master's degree in Architecture. It is a unit in which students study the various systems which produce the built environment, e.g., structure, building skins, air conditioning, plumbing, etc. and comparisons are also made with other systems such as the aerospace, automotive and shipbuilding industries. The course introduces students to advanced and futuristic concepts, while at the same time analysing traditional methods.

The first semester of the course is taught using a mix of lectures and drawing assignments, with teaching staff taking the lead and establishing the teaching paradigm. Roles are reversed in the second half of the year: students become the active leaders and staff take the roles of advisors and critics. This section of the course is totally computer-based.

Objectives and Implementation

The following excerpt from the application for the Action Learning Project grant describes the course objectives and proposed implementation:

Objectives

1 To make a direct comparison between conventional and computer based teaching methodologies;

2 To optimise the available time to cover as many aspects of Building Systems as possible;

3 To increase students' depth of understanding of the systems;

4 To apportion work to different groups so that parallel programmes can be achieved;

5 To make a comparison of the difficulties encountered by stand-alone groups compared with groups working on related projects;

6 To explore the effectiveness of peer teaching and group interaction;

7 To evaluate the effectiveness of the interactive multimedia, hypermedia, virtual reality and digital virtual design studio.

Implementation

In the 1994-95 academic year, four projects will be put forward for students to work on:

1 An interactive multimedia model of a Tang Dynasty Temple;

2 A multimedia presentation of morphing of structure;

3 A multimedia presentation of the erection of a curtain wall system for a high-rise building;

4 A multimedia presentation of an interactive programme for building maintenance for a high-rise building.

Topics 3 and 4 are directed towards the same building and the two projects are to be hyper-linked. Data for topics 1, 2 and 3 have been supplied by outside sources.

A number of interactive multimedia projects already exist, developed by staff and students in previous years of the Building Systems course. The most complex and complete of these is Temple Tutor — a set of interactive multimedia models of traditional Chinese temples (Bradford and Will, 1992).

Students will be required to proceed from pen and paper storyboards to 3D computer models produced at SGI workstations. This will be done as group work and the progress of each project monitored in weekly presentation sessions with the models presented on a CRT projector for analysis by the entire class.

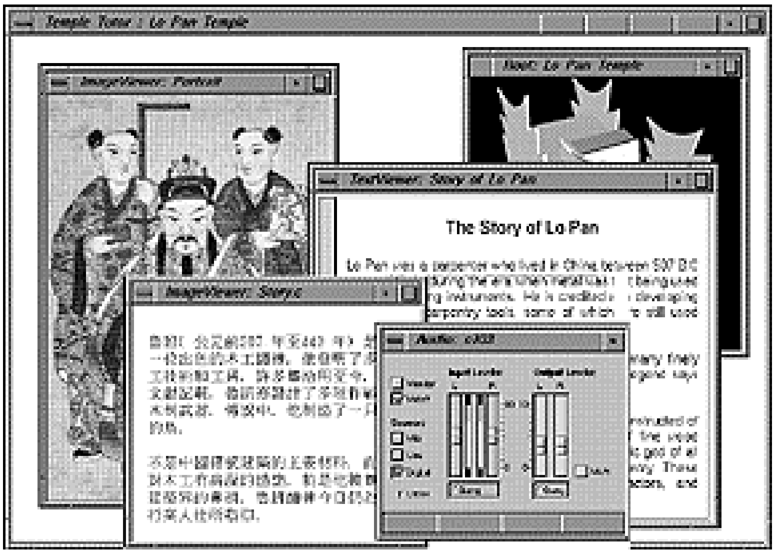
The Computing Environment

The Multimedia Lab

The Department of Architecture's multimedia laboratory incorporates a network of fast Silicon Graphics workstations together with a variety of input, output and display devices which include video, flatbed and slide scanners, b&w and colour printers and a 3-tube CRT projector for display of both computer output and video. The system uses digital ASCII text, audio, images, drawings, videos, animations and 3D models.

The standard multimedia elements of text, audio and bitmap images are available, and delivery is via a separate X-Window viewer for each medium. Figure 1 shows a 3D temple model with a bilingual TextViewer window and the AudioPlayer control panel. Highlighted Chinese characters in the TextViewer indicate hyper-links to additional information about the topic represented by the character. Links could be to further text or images, or to a spoken commentary or music presented via the AudioPlayer.

Figure 1: Page from Temple Tutor



All of the other formats necessary for multimedia are also present. These include drawing programs such as AutoCAD; movie and modelling software such as Movie Maker, 3D Studio and Wavefront; and hypermedia presentation programs such as Showcase and HTML.

Research Project

The research project set out to investigate the following, open-ended question:

> In a problem-based, computer intensive environment, what is the nature of the interaction between student characteristics, computers and learning?

The preliminary part of the project took place over a four month period in the second semester of the Building Systems unit: between January and May of 1995. Follow-up interviews were conducted in January 1996 with eleven of the original students who continued with Building Systems II, and finally in May 1996.

Funding from the Action Learning Project was used to employ a research assistant, Ms Yung Wai-ling, who worked with the team organising interviews, setting up equipment, translating and transcribing tapes and filing and indexing the on-line and off-line data. The team collected a variety of primarily qualitative data over the course of the study: text-based data from interviews and observations; and non-text material such as videotapes, audiotapes, questionnaires, mind-maps and semantic networks, sketches, storyboards and photographs.

The interviews, consisting of more than 17,000 text units, were indexed and analysed using NUD•IST[1] (non-numeric Unstructured Data – Indexing, Searching & Theorizing) a qualitative research tool developed originally for the social sciences. NUD•IST was the primary cognitive tool for data analysis.

Sources of Data

Student Characteristics

Individual student profiles were built up using a suite of tools:

Approach to Learning: The Study Process Questionnaire

The SPQ is the Hong Kong tertiary version of a questionnaire developed by Biggs (1992) first in Australia then in Hong Kong. It provides a profile of each student according to his/her predispositions to learning on three scales: Surface Approach, Deep Approach and Achieving Approach. Students were tested in the first weeks of the term.

An additional reason for using SPQ in this study was to provide a comparison between our students and Hong Kong students in general. The results demonstrated that the class average scores were typical, when compared with Biggs' *H4. University General (higher years)* scale, however there was a great deal of variation within the class. Figure 2 illustrates one student's SPQ profile, graphed as a deviation from the H4 norms: the graph illustrates a comparatively high score on surface strategy, a score in the top 10% on deep motive and scores below the norm on achieving strategy.

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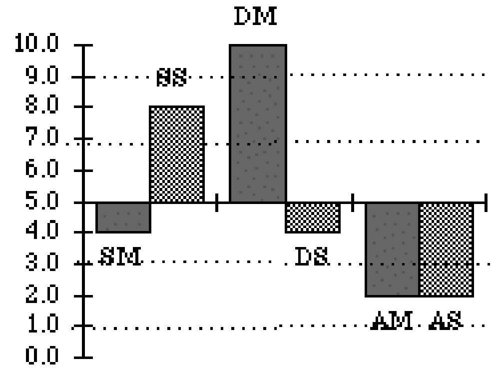
[1] NUD•IST is copyrighted by Qualitative Solutions and Research Pty. Ltd. and is distributed internationally by Sage Publications, 6 Bonhill St., London EC2A 4PU, UK.

Figure 2: SPQ score as deviation from Biggs' H.4. norm



Computing Knowledge: (a) Mind Maps

The technique of 'mind mapping' as described by Buzan (1993) proved to be a productive method of dealing with unstructured data such as videotapes and open-ended interviews. It was used throughout this study as a means of developing a picture of computing skill and resulted in the creation of basic nodes for the NUD•IST indexing system The technique involves identifying key concepts, looking for links between them, and developing these links into a branching structure from a central concept.

Figure 3: Mind map of one student's computing knowledge

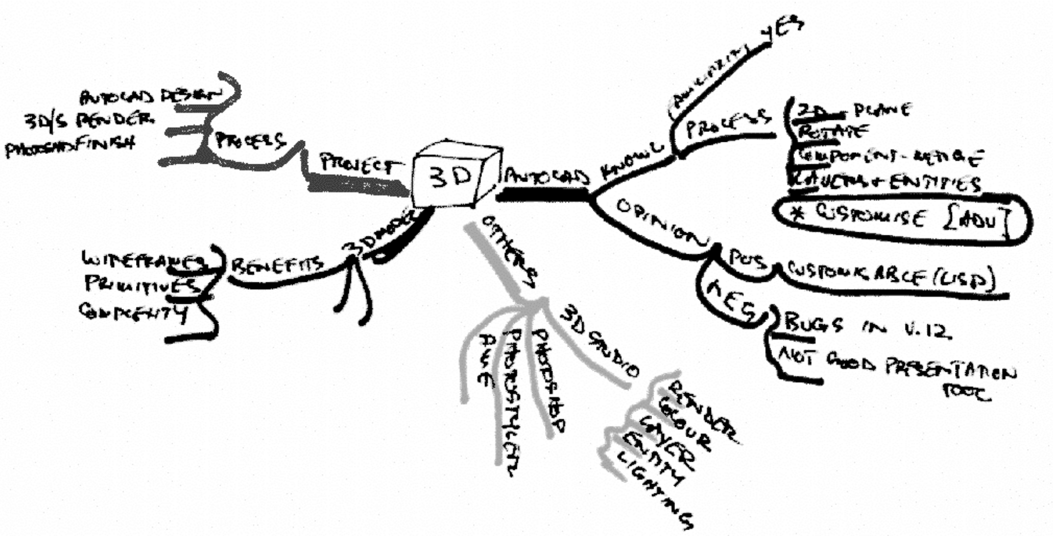


Figure 3 illustrates a mind map derived from one student's demonstration of 3D computer modelling: the 3 o'clock branch divides into categories of knowledge about AutoCAD; 5 o'clock represents knowledge of other computer programs, such as 3D Studio, Photostyler and AME; 7 o'clock lists benefits of computer modelling in architecture; and 9 o'clock categorises ways in which computing will be used in the coming project.

Computing Knowledge: (b) Mental Models of the Server

Another form of graphic representation was obtained when the researchers asked the students to draw their 'mental image' of the server and indicate the position of their files. This was at a time when students were experiencing particular difficulties with file loss. Figure 4 shows a reasonably accurate hierarchical model produced by one of the group leaders, indicating that she has a clear picture of how the system works. By contrast, Figure 5 is from a student clearly having difficulty comprehending the system — it is a rather whimsical attempt to anthropomorphise the computer into a representation of a human brain (complete with eyes).

Figure 4: Mental model of server (accurate)

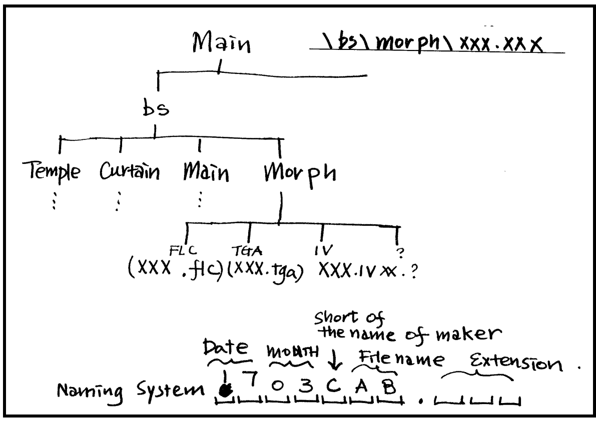
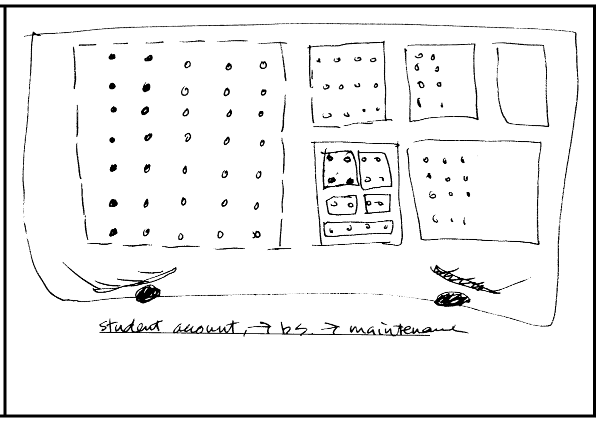


Figure 5: Mental model of server (whimsical)



Structural Knowledge: PFnets for Concept Mapping

Pathfinder networks (PFnets) result from semantic association tests in which subjects are asked to rank the 'relatedness' of pairs of concepts. The resulting output is a graphic representation of the subject's concept map of a group of terms. It is a technique more commonly used with market research, but it proved to be a valuable tool, particularly when followed up by an interview in which the student was asked to interpret the resulting 'network'. The software used to produced the PFnets was KNOT[2].

Students were asked to do a semantic comparison test using 11 words which had been distilled from earlier interviews and had all become low-level nodes in the NUD•IST data base (me, my group, computer, software, presentation, calculation, modelling, creative, research, learning, memory). The aim of the exercise was to see how closely students related computers to themselves and their group as well as to concepts such as creativity and learning.

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[2] KNOT is available from Internink Inc. P.O. Box 4086, Las Cruces, NM, 88003-4086 USA.

Figure 6: PFnet produced by KNOT

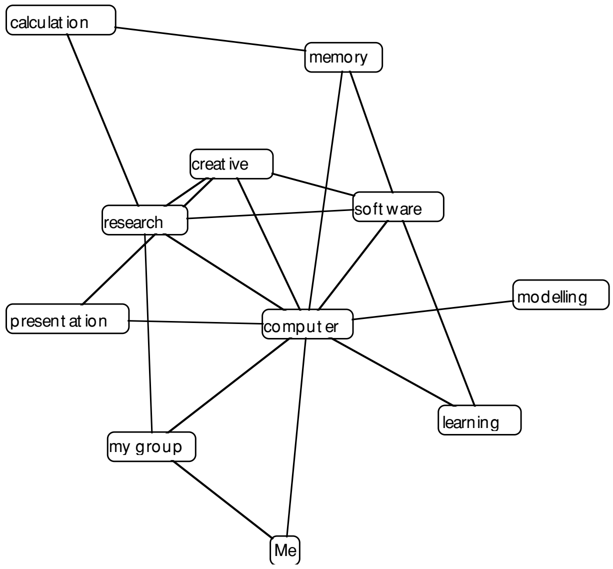


Figure 6 is an example of one of four characteristic network shapes identified in thie exercise. It is from a student who sees computing as central to his work and relates all other concepts to this.

Learning

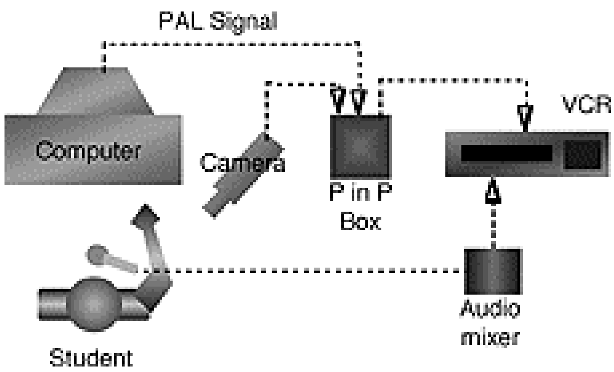
The Building Systems course was problem-based where students worked in groups to create new knowledge, in the form of interactive multimedia presentations. Learning was seen as a constructivist process; therefore the evaluation of the learning experience could not be accomplished using tests of declarative or even procedural knowledge. The research team collected data continuously over the course of the term, using a variety of techniques:

Video Observation

Class meetings and project demonstrations were covered on videotape using a Sony Video 8 Handicam with 12x zoom lens and built-in and extension microphones. Two types of set-up were used: hand-held (which proved technically difficult and was mainly employed for reference only) and fixed p-in-p.

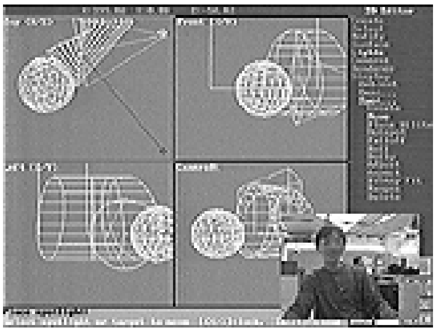
The most satisfactory result was obtained by recording directly from the SGI computer through a video converter onto the Handicam and combining this signal with the image from a fixed camera using a 'picture-in-picture' device. The connection diagram is illustrated in Figure 7.

Figure 7: Connection diagram for video observation system



The *p-in-p* system was adjusted so that the computer screen comprised the main image and an image of the student was superimposed in one of the four corners. Figure 8 shows the student's image positioned at the lower right of the frame as this is normally the least used area of the screen in graphic work.

Figure 8: Output of p-in-p device



Video Transcription

The videotapes were logged using a computer program called 'C-Video'[3], which enables the replay of the Sony Handicam to be controlled directly from the Macintosh numerical keypad by means of a cable between the computer's serial port and the LANC remote control plug on the Handicam. C-Video produces a text file which can be introduced directly into the NUD•IST data base, and enables time stamping of the transcript.

Audiotaped Interviews

The later interviews as well as interviews with teaching staff were recorded using audio only. Interview sessions were conducted within a period of one or two days if possible in order to provide some uniformity between them. The interviews were conducted in an office off the laboratory or in a staff office and were fairly informal and open-ended although a list of questions had always been prepared and were always asked — though not necessarily in the same order.

Process Documentation and 'Off-line' Material

'Off-line' material included both 'process documentation' such as notes kept by developers and evaluators, incident reports, minutes of meetings, etc. and all non text media such as students' preliminary sketches, storyboards, etc. as well as scans, photographs, videotapes, screen captures, audiotapes, mind maps, etc. These were logged and indexed in the NUD•IST data base together with their locations and formats. As much as possible of this material was converted into electronic form and stored on disk for easy reference — e.g., Figure 8 is one of a set of screen captures, or 'key frames' made to accompany transcripts of videotaped sessions. Figure 9 is a detail from a computer scan of a preliminary storyboard.

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[3] C-Video was developed by Jeremy Roschelle at U.C. Berkeley and is distributed by Envisionology, 4104 24th St, Suite 344, San Francisco CA 94114, USA.

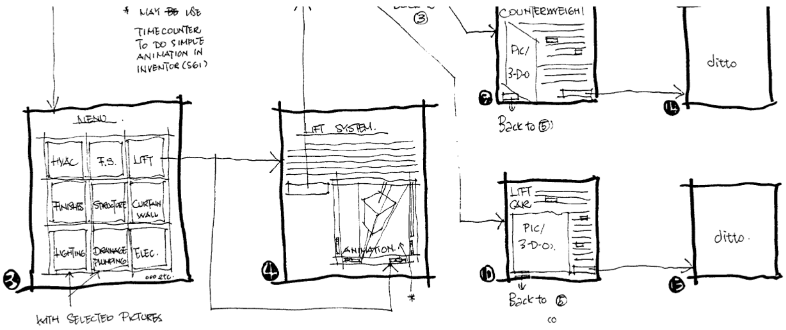

Figure 9: Detail from first storyboard for the Maintenance project

Outcomes of the Study

Student Projects

The four interactive multimedia programs described in the grant application were produced according to plan, although a network system crash late in the term resulted in significant loss of data and none of the projects were completed by the due date. The research team, however, was more concerned with process than with product and the observations conducted throughout the term had provided a wealth of information on the progress of cognitive construction, the levels of metacognitive awareness and the operations of distributed cognition.

Research Paradigms

The project demonstrated the value of qualitative, data-driven research methods for studying rich and complex learning environments. By choosing not to operate with the restriction of a hypothesis which defined the type of data to be collected, we were free to accumulate whatever information was available and appeared to be relevant at the time (interviews, storyboards, videotapes, screen captures, mental models, timetables, etc.). This pool of heterogeneous and unstructured data was then refined and organised through the use of established qualitative research methodology such as grounded theory (Strauss and Corbin, 1990), data reduction (Miles and Huberman, 1988; Miles andHuberman, 1994) and theory-building (Richards, 1993; Richards and Richards, 1992) in order to produce results which could be tested both internally for consistency and externally through triangulation with other results.

This approach resulted in some unexpected outcomes which we hope to pursue further in future research, e.g.

- The picture-in-picture *(p-in-p)* video system, developed for this project to observe the progress of students working on computers, is of obvious value for research in the wider field of human-computer interface design.
- The use of PFNets to elicit descriptions of structural knowledge shows great promise and after further investigation using a larger sample, will be written up separately as a journal article.
- NUD•IST, originally designed as an instrument for qualitative research in the social sciences, has proved to be an invaluable cognitive tool for the structuring of data about learning.

Paradigms of Learning

The study has reinforced the relevance of qualitative paradigms of learning in university level professional education: constructivism, PBL, structural knowledge, etc. The interviews consistently demonstrated that the most metacognitively aware students preferred to see learning as a constructivist (as distinct from instructivist) process. This was demonstrated clearly by the ways in which students reacted to the two halves of the Building Systems course. The first term comprised a series of lectures, assessed by examination, wherein students were required to be passive learners and to rely on memory. In the words of a Canadian-educated student:

> ...In Hong Kong if you can memorise it well then you do OK. This is what I don't really agree with. In terms of learning... They shouldn't just require you to have a good memory. It doesn't mean anything after the exams if you can memorise it and then forget everything.

It could be inferred from this that a causative factor behind some of the surprisingly high surface strategy (SS) scores on the Study Process Questionnaire was the reliance on examination to assess the first semester of the Building Systems course.

In the second half of the year students were offered the opportunity to design their own learning. The resulting projects are vivid examples of how the students literally constructed 'new knowledge' in the form of interactive presentations directed at explaining complex structures and concepts to a third party. The exercise involved them in researching and developing their own insights into domain areas (structures, history, components, design) and computing (software, working methods, production techniques).

Computers as Cognitive Tools

This project provided the opportunity to study the effectiveness of computers as cognitive tools in architecture education. The assumptions underlying this approach to teaching professional courses were corroborated by the study. The students acquired a range of new skills and developed innovative ways of approaching the tasks of designing structures, testing their ideas and communicating with peers and clients. In addition they came to appreciate the 'affordances' offered by computers for their project work and ultimately for their futures in the architecture profession.

While many of them found the course of study difficult and the learning environment frustrating, in retrospect (12 months later) most expressed positive opinions about the experience. Much of their frustration was caused by the crowded curriculum and the competing demands of the timetable. The Architecture faculty has recognised this by extending Building Systems into a two-year course. The Faculty has also made a considerable financial investment in enlarging and equipping the computer laboratory so that more students can take advantage of working in this environment.

Defining Student Characteristics

In the course of this project we employed a battery of student profiling tools to supplement the naturalistic data from sources such as open-ended interviews and observations.

Study Process Questionnaire

In Biggs' (1992) view, the ideal learner is characterised by a *deep-achieving* approach, which combines:

> ... wide reading, discussion with teachers and other students, playing with the task, thinking about it constantly... (and) being self-disciplined, neat and systematic; planning ahead; allocating time to tasks in proportion to their importance, keeping clear notes, and all those other planning and organisational activities referred to as 'study skills' (pp. 11-12)

While the averaged SPQ scores from the class correlated closely with Biggs' normed cluster for senior university students, within the class there was a great deal of individual variation: e.g., there were some initially surprisingly high scores on *surface approach*; but there were also some extremely high scores (top 10%) on *deep motive* and *strategy*. The SPQ profiles of the most successful students in the class contained high scores on *deep motive* and average to high scores on *deep strategy*, but not necessarily average or high scores on either of the *achieving* scales.

Computing Knowledge

In the late 1990s, a basic knowledge of computing has become a prerequisite for study in virtually every profession. In computationally intensive professions such as engineering and architecture, computer software packages such as AutoCAD have redefined work practices as well as the means of storing and transferring information. For students in these disciplines, knowledge of specialised software packages has become as important today as was mastery of the slide rule or logarithmic tables 20 years ago.

We examined students' knowledge of the range of computer applications which are useful for the production of 3D computer models and characterised the necessary knowledge and skills under three headings:

- **declarative** knowledge (knowing *that*) describes what the student knows about the interface and the functions of the various tools for producing a desired output;
- **procedural** knowledge (knowing *how*) describes the skill with which a student uses the computer tools to produce the desired result;
- **contextual** knowledge (knowing *where, when* and *why*) describes the student's knowledge of the criteria necessary to select appropriate software and hardware to achieve a desired result.

The computing knowledge profiles demonstrate, when compared with other measures and course results, that declarative and procedural knowledge may not be as significant as contextual knowledge in predicting success. On the whole, students do not regard practical computing skills as essential for success in architecture and many find it difficult to reconcile a computer's prescriptive interface with the flexibility required for creative design. On the other hand they value the computer's accuracy and speed and the 'affordances' it provides in calculating perspectives, replicating complex shapes and facilitating experiment and simulation.

Structural Knowledge

Jonassen, Beissner and Yacci (1993) regard structural knowledge as the essential link between declarative and procedural knowledge. In this study structural knowledge emerged as the central element in a student's ability to reconcile the sometimes conflicting demands of creative design in a computer-intensive environment. Students with clearly developed structural knowledge were better able to function in the Building Systems environment: to apportion their time, to use productive strategies and to work in groups; in fact the students with the most highly-developed structural knowledge tended to be the group leaders.

Metacognitive Awareness

Awareness of the processes of learning and knowing emerged as a central ingredient of success in this collaborative, computer-intensive learning environment and the metacognitive issues which were thrown up from the data include attitudinal factors such as enjoyment or dislike of computing, PBL and collaborative learning, as well as self-knowledge and task knowledge.

Long-Term Outcomes

The 3D computer modelling begun in the 1994-95 Building Systems course for this project has been continued by subsequent cohorts of students until at the present time (September 1997) a considerable body of student-created resources have been produced covering high-rise buildings (construction, services, regulations, light simulation, etc.) as well as 3D models of historical Buddhist architectural styles and construction techniques.

The Department of Architecture has taken note of the outcomes of this project and there has been a noticeable shift towards the increased use of powerful computer tools in all aspects of the curriculum, accompanied by significant expenditure on computing laboratories. The most recent purchase has been a virtual reality engine on which to mount and display three-dimensional models. Recent educational initiatives range from compulsory units in Computer Aided Design for students in Year 2 of the undergraduate degree, through the development of digitised pictorial data bases of historical material on Hong Kong and China, to advanced units on virtual reality modelling.

Another powerful cognitive tool for Architectural education has been the World Wide Web, providing opportunities for Architecture students at the University of Hong Kong to collaborate on projects with students in other countries through the Virtual Design Studio program.

Computer-based design and 3D modelling software are now key tools in the Architectural design and construction process and the skills to use them effectively have become essential components in Architectural education. This project has provided invaluable data on how these tools can be integrated into the curriculum: emphasizing the importance of the student-centred approach of learning *with* computers, rather than the more conventional CAI approach of learning *from* computers.