Teaching Concepts Utilizing
Active Learning Computer Environments

by

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Massachusetts Institute of Technology, 1998
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Submitted to the Department of Civil and Environmental Engineering
in Partial Fulfillment of the Requirements for the Degree of
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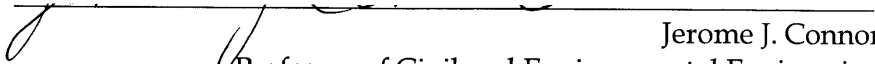
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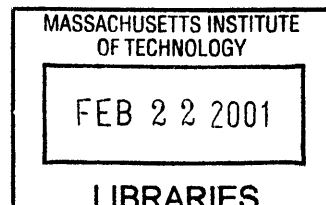
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Abstract

Teaching conceptual and qualitative material well is generally considered lacking in undergraduate engineering education. The education of structural engineers, in particular, overemphasizes the role of structural analysis. This thesis proposes a solution to encourage conceptual understanding through effective interactive computer-aided learning tools. The approach emulates a tutor to engage the student in a one-on-one active experience, utilizing components of multimedia, simulation, and interactive exercises. The student is forced to engage in conversation as she proceeds along a narrative path for a specific conceptual topic. Fully controlling the student's progress ensures she interacts appropriately with the material and yet still allows a sense of experimentation. The essential key in creating an environment having effective engagement is the provision of continuous deep feedback tailored to the student's own interaction with the material.

This thesis presents a methodology for building effective learning experiences. The full building process is included: design, implementation, test. This methodology is formulated, a prototype module is created within the teaching context of structural behavior, and this module is then evaluated rigorously for effectiveness in the classroom. Also included is a review of current criticisms and desired qualities of structural engineering education and the basic pedagogy for learning.

Thesis Supervisor: Jerome J. Connor
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Chapter 1

Introduction

A new paradigm has emerged in undergraduate engineering education in order to rectify the recognized overemphasis on the teaching of analysis versus behavior and synthesis. Advocating this new paradigm, this thesis offers an approach for building effective interactive environments to improve the learning of concepts by elementary students. The underlying hypothesis for this approach is:

> *a well-structured and computer-aided learning experience that for conceptual material,*
>
> - *emulates a tutor with a narrative and contextual thread,*
> - *encourages learning by discovery,*
> - *gives practical, real-world connections to this learning, and*
> - *provides specific and continual informative feedback on the student's actions*
>
> *will achieve deeper understanding of both the given material and the quantitative classroom material*

This document describes the effort involved in implementing this approach within the context of structural engineering and behavior. The work follows the flow of a typical development process with the three critical phases of conceptualization,

implementation and evaluation – design, build, test. Each phase is a necessary component of the research. The presentation is organized as follows. Firstly, Chapter 2 discusses further the motivation and the current problems with engineering education, identifying the basic pedagogical requirements for an effective learning environment and reviewing precedents of similar work. This discussion then culminates in the introduction of the proposed solution for the learning environment and its design requirements. Chapter 3 presents the conceptualization phase and the critical outcome: a methodology for building such an effective learning experience. Chapter 4 describes the process of implementing it through a prototype module. Lastly, Chapter 5 discusses the evaluation process, which involved a range of students from various engineering and architectural schools.

Information technology (I.T.) is adopted as the technology for enhancing the learning experience. Computers offer ease and cost effectiveness. With strong dynamic figures or simulators, concepts and ideas can be conveyed instantly. Previous means for achieving the same result would have included large expensive laboratories, etc. The reader may defend these old style experiments for their physical and practical experience; however, the same is anticipated of a well-developed computer package if pertinent images and practical examples are included to provide context to the simulation. Such an approach allows access to so many more users, with the convenience of continual access and repeatability.

The learning environment's ease of use and visual interest is essential to ensure the user stays with it to continue learning. Various other computer simulators and teaching tools are already available on the market. However, many of these previous packages lack two important factors – a well-annotated and guided context and correct emphasis on behavior. This methodology takes the learning environment beyond being just a simulator. Emphasis is placed on effectively integrating simulators with strong images, text and examples to provide a more complete environment with context and practicality. The product should be more than the sum of its parts. Achieving an "interactive learning environment" is challenging and time consuming. This thesis

proposes the steps to make the development process easier and the final product more effective.

Before proceeding, definitions of certain terms are clarified.

1.1 Definitions

Some of the popular terms bandied about in education today have acquired overuse and thus, cloudy meanings. Therefore, in an effort to avoid this further, the truest and ideal definitions of three such terms are below. These three terms are quite similar yet they have some subtle and important differences. All of them are used extensively in the research's discussion and outcomes.

1.1.1 Interactive

"interactive: 1. Reciprocally active; acting upon or influencing each other
2. Pertaining to or being a computer or other electronic device that allows a two-way flow of information between it and a user, responding immediately to the latter's input."
from the Oxford English Dictionary (O.E.D.) [26]

Interactive is a particularly popular term. Everyone is claiming their tools or websites to be so called "interactive", but usually they are merely an experience of one-way information transfer as the user aimlessly clicks buttons to pass through it; no effort is provided to force mental engagement. The meaning adopted by the thesis is in accordance with dictionary definition above –*"acting upon or influencing each other"*.

1.1.2 Active Learning

"active: Originating or communicating action, exerting action upon others"
O.E.D.

Though similar to interactive, this term is more specific to learning approaches and implies engaging the student in the material through action. In the classroom, this usually means involving the students with discussion and activities to encourage

mental engagement on the topic and allow immediate peer and instructor feedback.

Research has demonstrated such learning techniques to be more productive, more stable and more efficient than passive forms of learning, such as listening to lectures (Laurillard [17], Breslow [6]).

1.1.3 Adaptive Learning

> *"adaptive:*   *Characterized by, or given to, adapting things to a purpose, or oneself to circumstances*
>
> *adapt:*   *To fit (a person or thing to another, to or for a purpose), to suit, or make suitable."*
>
> <div align="right">O.E.D.</div>

Thus, adaptive learning is an experience that adjusts as the student progresses to cater for the level of understanding their demonstrating. The subtle difference between it and active learning is that it implies a much greater level of intelligence and personal attention from the instructor or computer to be able to provide such specific tailoring. Therefore, to achieve such sophistication with I.T. is extremely challenging and the source of much research. With people, it merely requires a good an patient tutor.

Furthermore, when applied, it usually applies the ideas of active learning and then extends upon them.

Chapter 2

The problem and a proposed solution

This chapter presents the motivation for developing new approaches for conceptual learning. Section 2.1 establishes the need for such an approach through a literature review of the current problems and changes in civil engineering undergraduate education. The most common theme was to place more emphasis on behavior. Teaching tools may offer a solution.

In order for a tool to be effective, it must meet not only the "engineering" needs but also the pedagogical requirements. Section 2.2 reviews the appropriate pedagogical theories for developing such a learning experience. This knowledge helps to highlight the problems with current practices as well as setting the ground rules for the learning methodology to be proposed.

Information technology (I.T.) was quickly identified as playing an important role in the solution. A discussion on its contributions is presented in Section 2.3.

Examining precedents, previous attempts to develop tools with similar goals to this

thesis (conceptual learning and/or innovative learning tools) were examined. Section 2.4 discusses these examples, considering their pros and cons and their influence on this research.

Finally, based on a consideration of all these concerns and influences, a methodology is formulated in Section 2.5. This methodology is then explained in full in Chapter 3.

Therefore, this chapter presents the background issues and motivation for this thesis, which allows the design problem to be clearly defined and a potential solution to be proposed.

2.1 A need for change: problems with engineering education

Internationally, professional engineers have raised a strong concern that the amount of structural behavior in their undergraduate education is insufficient. As the computer's role continues to become increasingly pervasive in the structural engineer's office, the risk of this problem will only be heightened. The current availability of inexpensive personal computers and powerful software now allows computers to be utilized by structural engineers for the majority of their analysis and design calculations. Major problems could be created if the person using the computer does not interact appropriately with the program to ensure the structure will *perform* its final function as intended. This responsibility of the user depends on their ability to go beyond just analysis to truly understand structural behavior and its implications.

2.1.1 Industry's point of view

These claims on the level of structural understanding of current graduating engineers are harsh. What evidence for them is there? Most are based on general observations by professional engineers. One such engineer, Morreau [22], formulated criteria for his observations. His assessment measures were:

1. How successfully do the graduates model the structure prior to analysis?
2. How successfully do they interpret the results of the analysis? Do they recognize the errors in these results? and

3. How successfully do they use the analysis to modify the structure?

He found that students generally cope with the first measure quite effectively, especially when posed with a straightforward problem, i.e. when the whole framework can be modeled on the computer. Their inadequacies begin to show in all three measures, however, once the problem needs to be broken down or the boundary conditions are not obvious – essentially, when the engineer really needs to understand how a structure is working.

At a more rudimentary level, Brohn [7] observed in students a poor ability to just sketch the approximate bending moment, shear force, reactions and deflection solution to a structure. He came to the reasonable conclusion of equating these inabilities with a lack of understanding of structural behavior. Whilst, after a review of typical subject matter in analysis and design courses in the United States, Bjorhovde [1] complained that a graduating student too often had a limited practical appreciation of design and engineering. He questioned if their education covered too much theory, or were the students instead being trained to become handbook engineers, without a solid training in the engineering principles.

The conclusive argument from Industry, therefore, is that if there is a problem in the product – the graduating structural engineer - then there must be something wrong with the process - the education system. They make a call to the educators for change in the system with more equal emphasis on analysis and, behavior and synthesis;

> *"A fundamental connection exists between civil engineering and creative, imaginative though... Current engineering education programs do not recognize that civil engineers need and use creative, "right-brained" thinking skills as much or more than technical skills."* Feldsher [12].

2.1.2 The educator's point of view

Putting great emphasis on the technical skills – structural analysis – by crunching numbers and assessing results is currently the most common method of educating engineers. Yet, to better understand the role of analysis in Structural Engineering, consider a definition of it. From Wright [37],

structural analysis is *"the process by which the structure and its environment are modeled to predict structural response."*

From this, both the difference and the link between analysis and behavior are seen. Teaching the structural analysis methods utilized in computer programs and hand calculations, often places much detail and weight on the mathematics and equation manipulation and forgets about the "response" being predicted. This leads to the students learning these techniques, yet hardly ever connecting the analysis outcomes with how structures actually physically behave. More importantly, the students do not develop their synthesis skills.

Engineers are designers, however, and design consists of both synthesis and analysis. For instance, such responsibilities and tools of synthesis that also essential to be learnt by the budding structural engineer include selecting the appropriate technique to model a structure and its environment, interpreting the analytical results for assessment of the behavior of the actual structure, and making decisions and assessing their impact for the design, construction or use of the structure. Generally, there is little intrigue and, hence stimulus, for the structural engineer in correctly manipulating an analytical model, especially with the current power of computers, yet it is the manipulation that is often the primary focus of structural engineering courses. Department head, Professor Bras concurs with this, commenting in the MIT Civil and Environmental Engineering (CEE) newsletter, Spring '94 [4],

> *"...I do feel that engineering education many times fails to challenge the imagination of our students. Many fail to experience the uncertainties and vagaries of problem solving in a world with no one answer".*

In response to the Industry's call, the movement amongst educators for change in engineering education is swelling. MIT's own CEE department, in particular, has recently undergone substantial change to its curriculum to redress the balance of synthesis and analysis. Prof. Einstein explained the reasons for these recent changes in the report from the ECSEL(Engineering Coalition of Schools for Excellence in Education and Leadership)/MIT Engineering Education Workshop '99 [9], as

> *"recognition by faculty that our education was unsatisfactory and inadequate... our graduates were not able to conceptualize... and whatever creativity they had was often*

stifled.."

Other schools who are a part of the ECSEL program are also undergoing such change. Similarly, many other educators have voiced their concerns, all with a common theme that complains of the emphasis on analysis over synthesis and behavior, and the resulting lack of creativity. As evidence, a selection of recently published views on the topic follows:

> *"..we have lost much of the creativity. Engineering education must seek a new balance between analysis and synthesis and find ways to promote creativity and risk taking"*
> Bras, the MIT CEE newsletter, Spring '99 [5]

> *"...I believe we have underestimated the importance of encouraging and nurturing the creative instincts that exist in everybody, and particularly in those who aspire to the heights of engineering. The ability to seek a creative solution, to synthesize, to be imaginative is a property we should cultivate... traditional engineering courses do not encourage creativity... it is important that design is a key part of our curriculum."*
> Newland, head of the Engineering Department, University of Cambridge [23].

> *"emphasis on abstraction and analysis at the expense of synthesis... detrimental with regard to the professional careers of our students"*
> from the MIT CEE department's report to the visiting committee in Sept. '98 [11]

In summary, it is clear from both the engineers and the educators that a new paradigm of placing strong emphasis on teaching structural behavior and synthesis is being asked for. This change wants to see concepts taught, creative instinct nurtured and an exposure to the vagaries of design and real-life.

2.1.3   The dilemma

Computers are often blamed for the degeneration of a student's practical understanding of structures (Petroski [28]), yet it is well acknowledged that it is the computer's increasing and ultimately dominant role in analysis, design and drafting that is forcing a new exciting paradigm. Computer technology provides enormous and worthwhile potential in engineering education, though in doing so it demands radically new approaches. Brohn [7] recognizes this, citing the possibility that,

> *"a future review of the teaching of structural analysis might reveal that the student's detailed knowledge of the stiffness method is about as useful to a structural engineer as the ability to shoe horses to a modern driver".*

How does an engineer survive, though, without an understanding of the numerical analysis of structures?

So, in searching for a solution to the problem a dilemma is revealed. What is the right balance for teaching (i) the tools of today and (ii) the fundamental theories to adapt for the future? As Smith and Samson from Texas A&M [31] put it,

> "On the one hand teaching how to use available techniques to solve today's problems to the detriment of the theory and concepts behind them may results in engineers who cannot adapt to tomorrow's problems. On the other hand, those who leave the education system with only the theory and concepts may not be able to make the immediate contribution that employers need"

There is no easy answer to resolving this issue; instead, it is best dealt with through educated compromise during of the design of the curriculum and learning experiences. The first step towards being informed for such decisions is to understand the Industry's required skills of the engineers – for today and tomorrow.

2.1.4   Required skills of a structural engineer

Using the domain of structural engineering for the context of the thesis, an outline of the practical and fundamental capabilities that Industry desires in a good structural engineer has been prepared in Table 2.1. Many of these skills have been collected from Morreau's [22] and Fleming's [13] papers, both calling for change in teaching methods. Please note, the term *"predicting"* in this table implies the ability to find approximate and reasonable values, it does not imply rigorous calculation.

Ideally, the strength of understanding imparted through the goals of Table 2.1 will be to the level of instinct. This list of goals is broad and demanding, though if met will provide the powerful and necessary abilities of a structural engineer. It is the challenge of this thesis to develop an approach for building effective learning experiences to impart these goals or skills.

Table 2.1   The Goals for achieving a Good Understanding of Structural Behavior

Ideal Abilities:

- ascertain whether a computer model is correct; examining output, questioning if results are sensible and assessing where modifications could or should be made,

- understand and predict the effects of changes to a model,

- ensure that the correct models and approaches for structural analysis and design were chosen,

- allow back of the envelope calculations for preliminary scheme designs, and

- achieve some independence from the computer!

The skills required to achieve these abilities:

- differentiate between a structure and a mechanism, applying the requirements of both equilibrium and stability

- achieve a conceptual knowledge of geometric compatibility

- follow and identify load paths

- identify the various modes (tension, compression, bending, shear) by which the load is carried

- predict not just the deflected shape, but actually thoughtfully considering how the structure – be it beam, truss or frame – deforms under load

- predict the bending moment and shear force diagrams

- predict reactions for any type of statically determinate structure

- establish the member forces for a statically determinate truss

- develop and using influence lines for reactions, shear force, bending moment and truss member forces

- communicate this information through sketches

2.2   Designing for education: the pedagogical requirements

Unfortunately, professors rarely have the opportunity to gain formal training or guidance on how to educate effectively. However, with the resources and flexibility available to a graduate student, such training is possible and so was sought, to (i) ensure the learning tools developed here are pedagogically sound and (ii) to build confidence in the research.

The basic pedagogical theories and requirements for developing effective learning environments are summarized in the following subsections. Section 2.2.1 introduces two different primary theories to assist in designing a worthwhile educational experience: *Theory One* and the *Tutorial Cycle*. Both provide useful and complementary guidelines for the development process, as well as helping to highlight flaws in current engineering education learning tools. Section 2.2.2 then reviews a range of currently recognized secondary theoretical models that may be appropriate for adoption for the learning approach described in this thesis.

Much of the material presented in this section was initially gathered during the author's studies for her Master degree [29] by auditing a class, "T525: Developing Educational Experiences using Networks and Webs" [3], given by George Brackett at the Harvard Graduate School of Education. Since then, the author has completed the complementary course "T522: Education Software Design" [2], which was also taught by George Brackett. This course was an invaluable experience developing the essential knowledge that became the pedagogical foundation of this research.

2.2.1 Theory One

Theory One as given by Perkins in Smart Schools [27], simply says:

> "*People learn much of what they have a reasonable opportunity and motivation to learn.*"

Elaborating on this statement, Perkins reveals its implication through stating the bare basics for learning to occur:

- **Clear information:** providing not just the knowledge needed, but explicit goals and expected performances. Explanations should be clear and concise, and accompanied by monitoring of the students' understanding of these explanations,

- **Thoughtful practice:** allowing the opportunity for learners to engage actively and reflectively with the learning material,

- **Informative feedback:** giving clear, thorough counsel to students about their performance, assisting them in developing more effectively, and

- **Strong motivation:** using activities that are well rewarded; their being, either, interesting and engaging in themselves, or able to support other achievements that concern the learner.

In summary, therefore, if the student is supplied with clear information about her performance through examples and descriptions, offered time to practice and think about how she is approaching the material, then provided with informative feedback, and finally taught from a platform of strong intrinsic and extrinsic motivation, her outcome of learning is likely to be successful.

To expand beyond these minimum criteria, however, Perkins also considers a few extra ingredients to be desirable to teach for understanding and achieve deep learning. These five components – Generative Topics, Mental Models, Understanding Performances, Levels of Understanding and Powerful Representations - are the focus of research on current practice, and together are referred to as *"Teaching for Understanding"*.

Generative topics are central, rich, interesting subjects, which are often interdisciplinary. Being easily accessible, they encourage questioning and exploration by the student. Patterns of thought or mental models – the second element – are useful to consider and apply as they enable understanding, just as they too are developed through understanding. Providing students with the opportunity to perform activities that will reveal their depth of understanding, is useful not only to the teacher for monitoring but also to the student as it encourages deeper thought and provides confidence in their abilities. The students do not simply regurgitate facts but are allowed to explain, exemplify, apply, justify, compare and contrast, etc.

The fourth desired element is to use various levels of understanding. Not all students learn well through the same methods, so providing multiple ways to engage with a topic, i.e. recall of content, problem solving, inquiry, application of principles to discovery of new ideas, gives them each the chance to acquire knowledge through their best route. Additionally, it presents the lesson with more variety and in a more

stimulating environment. Finally, using representations, such as metaphors, both physical and mental, can be very powerful as they can express and concisely encapsulate essential aspects of a topic for students.

2.2.2 The Tutorial Cycle

The most effective learning environment available for a student is sitting one to one with a highly skilled tutor. This is no great surprise, but how can some of the characteristics of this situation be emulated through other learning environments. Brackett has developed the *Tutorial Cycle* in his classes, T522 and T525, to try to answer this. The theory proposes that every complete educational process includes all the elements of:

- Presenting information related to the goals,
- Eliciting student action toward these goals,
- Assessing the student's action,
- Providing feedback to the student,
- Offering strategic guidance to the student, and finally
- Managing and motivating the process.

Although, these elements may be presented in any style or order, they must be present for the learning to occur.

2.2.3 Beyond the Basics

The basic pedagogical requirements presented in the previous subsection, set a demanding but essential challenge. There are even more pedagogical approaches, however, to be considered in the design of a learning experience. Some currently recognized theoretical models, referred to as *Theory Twos*, have possible implications on the detailed design of this thesis' methodology. They are listed with their key elements in Table 2.2.

Table 2.2   Table of *Theory Twos*

Theoretical Models	Key Elements
Constructivism	Discovery of principles through guided experiment, Invention of alternate systems of doing things, Meta-cognition (thinking about thinking or doing).
Developmental Perspectives	Adapting "advanced" ideas to simpler contexts at younger ages, Making abstract ideas concrete through manipulables, Enhancing understanding of complex ideas through applications in familiar environments (simile, metaphor...).
Cooperative & Collaborative Learning	Group activity through task division and subsequent peer instruction, Creating collaborative teams who work out their own processes.
Motivation Theory	Enhancing opportunities for intrinsic motivation through responsive environments, Student involvement in teaching and assessment, Enhanced creative opportunities.
Multiple Intelligences	Offering multiple symbolic representations, Engaging many modes of sense and action, Acknowledges diversity of human ability and consequent need to diversify instructional opportunities.
Situated learning	Project orientation for concept and skill learning, Simulations and models, Analyzing real, relevant situations.

2.3 Information Technology as part of the solution

Information technology applied to its fullest is an interactive technology; it can be programmed to respond to a user's actions. Thus, I.T. plays an obvious role in the current paradigm shift in engineering education, providing a responsive environment that invites the student to act and then provides them with some response. Recent interest in this area of research is particularly high, with such initiatives as iCampus at MIT.

Furthermore, I.T. and multimedia bring the following strategic possibilities to education:

- improved presentation of visual material
- new modes of instruction
- better access to information
- ease and cost effectiveness
- greater potential audience
- access to distant resources
- enhanced opportunities for collaborative work
- individual interaction for students

I.T. allows flexibility and encourages diversity. In the report from an ECSEL workshop [9], one educator observed that their application of I.T. had involved two roles – one as a support, the second as a challenge. The first role is for students who do not quite "get it" through the traditional means so go to the technology for extra assistance, while others who do understand look to the tool to find even more challenge.

Even with this great potential of interactivity, unfortunately, I.T. is usually just used for information transfer. Therefore, it is the role of current and future research to change this, by developing interactive, student-centered experiences that fulfill the possibilities of I.T. This thesis is a part of this research, utilizing I.T. and offering a solution to the problem in engineering education described in Section 2.1.

There is a further important aspect to consider in adopting I.T. in education: students now expect it,

> *"Incoming students have an amazing increase in knowledge of I.T. or at least computer literacy therefore have greater expectations of it in school"*
>
> ECSEL workshop report

Thus, students through reaching their changing learning goals, demand a higher level of sophistication and diversity in their learning modes. Furthermore, as a part of the training for any engineer today, they must acquire fluency with computers.

On a final note, consider one of the first points Brackett made in his class T522, the goal of educational technology is to improve and enhance learning, thus in turn improving and enhancing teaching. The capabilities of the computer are a means, not an end, and as such are a part of a complex system. Therefore, it is important to ensure the technologies are always transparent and applied appropriately to add value.

2.4 Examples of Precedence

Various attempts have been made to develop approaches to deal with the need for teaching structural behavior and concepts. A review of these are presented here to demonstrate precedent, discussing how they met the demands of not just the identified problem in structural engineering education, but also the pedagogical basics of Section 2.2. How effective is their learning?

Dr Beam and Dr Stress [21]: A stylish and effective simulator, Dr Beam is a beam that can have various loadings and supports attached to it, creating infinite configurations, including multiple spans, spring supports and support movements. The results presented instantaneously are deflection, moment, shear and rotation. The simplistic representation of the results is essentially qualitative, yet the ability is still available to read values off directly, if desired. An accompanying textbook is designed to provide exercises and guidance for using the simulation appropriately. Thus, together the complete package is an interesting approach to using I.T. to teach structural behavior. Its flaws are that even with the book it needs more annotation and guidance.

Additionally, although the book does try to maintain a real world context, it still lacks stimulating connections to practical design experiences.

Motion Lab: Also a simulation tool, Motion Lab was developed by Wang [34] and Prof Connor as a representation of a multiple degree of freedom dynamics system under dynamic loading. The output is both visual and quantitative. Although extremely powerful, the simulator is also complicated, with an interface that provides little support. Therefore, it has found its best application for assistance with homework exercises for Prof Connor's graduate structural engineering classes. It is best for only the more experienced student.

West Point Bridge Designer [33]: "This software provides you with the tools to model, test, and optimize a steel highway bridge, based on realistic specifications, constraints, and performance criteria." It provides an enjoyable and visual simulation tool for designing truss bridges, within an intuitive interface. The fault in it, however, is that it doesn't provide good guidance to prevent the student's choices from being somewhat random, nor does it encourage reflective conceptual thought through highlighting key observations. Thus is it appropriate for experienced students, but not elementary ones.

A torsion learning experiment in the Strength of Material Lab: This CDrom-based lab manual is a high quality example of a multimedia learning tool. The paper [10] through which this example was found provides a very good review in itself of the many forms of computer-aided teaching tools that have been developed. All of them, however, including this Material lab, still lack the true interactivity, defined in Chapter 1

Brohn's "Understanding Structural Analysis [8]: This example is only a book (from 1984) yet it represents an interesting and informative approach, using a series of sketches with accompanying text, to explain the behavior of structures and build intuitive understanding. The ideas could be very well adapted for the I.T. environment, particularly those on presenting the concepts of frames and their behavior.

1.050 Solid Mechanics [20]: Taught by Prof Bucciarelli, this is the introductory structures class at MIT CEE. Using his own course notes and computer models, Bucciarelli presents the course with a strong conceptual and behavioral context. Students are expected to review notes before class, so the class time is available for more active learning, covering case studies, open-ended design problems and discussion. This example is broader than the previous ones, because in describing a class it presents an approach for a complete learning experience environment.

Referring back to the Tutorial Cycle, presented in Section 2.2.2, consider how these examples hold up as complete education experiences that provide all of the tutorial elements. The first three examples are simulations; their problem is that they do not ensure effective engagement by providing strategic guidance and informative feedback specific to the student and their actions. Research supporting such complaints is given by Njoo and de Jong [24], and Goodyear [14]. Furthermore, these examples do not explicitly encourage conceptual observations to better build the intuition of the expert. The fourth example, the multimedia tool, reflects a popular approach of today of high quality presentation, but it falls into the trap of being merely information transfer. It does call itself "interactive", however, to quote Laurillard [17],

> *"Frequently described as 'interactive', these forms do not ask anything of students, and do not require any particular form of thinking or processing on their part."*

Thus it fails the Tutorial cycle by lacking assessment of the student's action and informative feedback directly on this action. Finally, the last two examples are taken from different teaching contexts yet they present informative ideas and influences for the research of this thesis.

As a final observation, it is also important to recognize the change in needs and ideals of a learning environment during the undergraduate experience. Many of the simulations are perhaps ideal for unaccompanied design and exploratory exercises by experienced students. Yet, elementary students require much more rigorous guidance and focus to ensure they engage meaningfully with the tools. These simulations usually lack this guidance. In particular, they often have interfaces with far too many possible choices to be assured the student's focus is where it should be.

2.5 The proposed solution

Acknowledging a need in structural engineering education, a solution is offered – teach more on behavior and design, in essence encourage intuitive, conceptual and qualitative learning. This thesis describes the methodology for developing this proposed solution, applying the potential of I.T. and ensuring it is pedagogically sound. Furthermore, to ensure the contribution of this work is relevant beyond just structural engineering education, the methodology is developed for the more generic goal of qualitative learning and reasoning.

From the examples given in the previous section, building simulators is seen to be easy. Setting them in an effective framework of guidance is the challenge that has not yet been attained. In contrast, with the multimedia slideshows the challenge is providing deep and personal feedback to enforce engagement. Thus, the proposed solution is a tutorial experience that expresses the essential components of the Tutorial Cycle (c.f. Section 2.2.2) through an active learning environment that integrates the "play" opportunities of the simulator with contextual and complementary multimedia (graphics and words). The result is a conversation between teacher and student; the student sits down with the "expert" to be guided through a lesson. The environment's role is to complement and enhance the classroom experience.

The goal of emulating a tutor was chosen, because as Newland [23] recently commented when echoing the words of MIT president Julius Stratton from 1961:

> "the results of this approach have been dramatic... stimulating deeper thinking,...
> generating student enthusiasm"

These results were based on a number of engineering departments at MIT experimenting with small tutorial groups at the time. Such manpower today is unfortunately unthinkable, thus if there is some way to emulate the tutorial experience through I.T. and achieve results that are even just a fraction of the above success, then the work will be a worthy contribution.

A tutor steps the students through the material, taking into account their current

understanding and providing cross-connections and relevance. Laurillard et al [18] further outlined this structure of the tutorial approach as,

> *"Expressing the overall message, decomposing it into its constituent parts, setting up practical demonstrations of illustrative examples of each part, relating these back to their conceptual meaning and synthesizing the parts into the meaning of the whole message."*

Thus, the tutorial approach is the essence of the proposed solution and is achieved through a conversational and narrative thread that scaffolds and controls the experience. The focus is on students at an elementary level of the given topic, where the fundamental skills and building blocks are still being developed. The student is repeatedly kept working through the experience, gradually building confidence in a non-threatening environment.

The connections between the practical and "real world" with the analytical are realized via regular cross-referencing with other modes of representing the same information. Additionally, the environment does not focus on just teaching design "tools" or just teaching fundamentals, as was the dilemma discussed in Section 2.1.3. Instead, the methodology for developing the learning experience is non-specific and leaves the decision on what to teach and focus on up to the designer.

The final list of desired qualities and important aspects of the proposed learning experience is:

- allows multiple modes of representation
- provides practical and relevant context to classwork material
- combats students misconceptions
- encourages internalizing of thought through experimentation, practice and reflection
- adopts intuitive and transparent interface design (Lohr [19])
- uses principles of constructivism – exploratory
- applies self learning and in turn encourages life-long learning

2.6 Summary

This chapter covered a wide range of material in order to first, fully establish the motivation for this thesis and second, to provide the supporting evidence for the solution that is proposed and developed.

The problems that have been identified in engineering education and for structural engineering, in particular, were discussed. Further background material was then explored: precedents presented; influences and supporting knowledge covered. Lastly, a proposal to solve the identified problems with an active computer-aided tutorial environment for qualitative learning and reasoning was formulated.

Chapter 3

A methodology for building an active computer-aided tutorial to teach concepts

Chapter 2 proposed an approach for involving engineering students in qualitative learning and reasoning. This approach emulates a tutor to engage students in a one-on-one active computer-aided learning experience. Adopting components of multimedia, simulation and interactive exercises to achieve this experience, the tutorial absorbs students in a conversation, drawing them along a narrative path on a specific concept. Fully controlling the student's progress ensures her appropriate interaction with the material and yet still allows for a sense of experimentation. The essential key for providing effective engagement to this experience is the provision of continuous deep feedback tailored to the student's own interaction with the material.

This chapter steps through and presents in detail the methodology for creating effective interactive learning experiences, based on tutorial modules. Three important sources of knowledge were drawn on to produce this research – engineering, pedagogical and

Structural Engineering	▪ solid grounding in Structures and Design ▪ develop a focused curriculum ▪ examine the qualities of a good engineer ▪ understand the students' learning methods

Educational Theory	▪ satisfy basic pedagogical theories ▪ explore new alternatives...

Information Technology	▪ capitalize on new technologies ▪ adopt effective communication techniques

effective learning modules

Figure 3.1   The sources of knowledge and their contributions to the development of the methodology

technological. Figure 3.1 demonstrates the contributions of these knowledge sources. By compiling these skills, it is hoped that the resulting methodology, provides for the inexperienced a practical and comprehensive set of guidelines on how to build these learning experiences effectively.

Section 3.2 describes this methodology and how it was developed. First, however, to understand the design decision that went into this development, it is important to clarify the methodology's goals. Knowing these goals from the beginning will also avoid misunderstandings and facilitate its adoption in future applications. Section 3.1 presents these goals.

3.1 The goals of the methodology

Three types of goals were refined during the development of this learning approach and methodology: the learning goals, the pedagogical goals and the technological goals. As can be seen, each of these goals corresponds with each of the sources of knowledge shown in figure 3.1. Clarifying the goals, particularly the learning ones, ensures appropriate adoption of the methodology by others.

3.1.1 The learning goals

Four important learning goals are achieved through the approach's capabilities for training, experimentation and practice. They are:

1. for students to internalize the concepts they are engaging with,
2. to teach students to make intelligent choices,
3. to provide the opportunity to play with/explore a given phenomena, and
4. to encourage creative problem solving.

Achieving these goals will bring the desired impact on engineering education through improved learning. Additionally, as the students are encouraged in self-learning hopefully they are in turn being encouraged in lifelong-learning.

This research initially began due to concern with the ability of current simulations and computerized learning tools to provide the necessary framework to ensure the student is interacting appropriately and observing what they should be. Therefore, one of the driving forces for this research was the desire to develop a method for providing this framework and embedding the simulations into an environment that steers the student in a correct direction yet still allows the opportunity for "play" and exploration. As the work has become more developed, the needs of undergraduate students have become better understood; not all students need this structure. The carefully crafted and structured tutorial experience, even with its experimentation and simulation opportunities, does not allow the freedom of open-ended design projects popular in classes that are more senior and specialized. At that level, the students have typically matured, become more specialized and self-motivated, so they prefer self-exploratory web-like learning. Therefore, the appropriate audience for the modules developed using this methodology is students at an elementary or review level for the topic to be taught; this will typically be sophomore or junior.

3.1.2 The pedagogical goals

In Section 2.2, a basic introduction was provided on the pedagogical theories for creating effective learning experiences. The requirements of the primary theories,

Theory One, the *Tutorial Cycle* and *Teaching for Understanding*, were highly influential on the methodology presented in this thesis. They present the essential framework for the module's learning environment. If a design decision does not satisfy the goals of these theories then it must be changed.

Aspects of some of the secondary pedagogical theories from Table 2.2 are also adopted by the methodology – constructivism, motivation theory and situated learning. Constructivism, in particular, is a strong influence, as allowing the students to learn by discovery is one of the central techniques the module employs. Furthermore, just providing this learning experience as an alternative to the traditional engineering learning modes of lectures and problem sets acknowledges the students' differing learning styles. These tutorial modules offer new and additional learning modes, increasing the students' learning "bandwidth".

A summary of these pedagogical goals is provided in table 3.1.

Table 3.1   Summary of pedagogical goals: the requirements of the primary theories

Theory One	*The Tutorial Cycle*	*Teaching for Understanding*
• Clear information • Thoughtful practice • Informative feedbackStrong motivation	• Presenting information related to the goals • Eliciting student action toward these goals • Assessing the student's action • Providing feedback to the student • Offering strategic guidance to the student • Managing and motivating the process	• Generative Topics, • Mental Models • Understanding Performances • Levels of Understanding • Powerful Representations

3.1.3 The technological goals

On a technical level, there are two main goals:

1. to keep the adopted technologies transparent.
2. to build the tutorial environment and achieve its interactivity with a low sophistication of technical skill.

The second one, in particular, should make the approach and methodology easily adoptable by educators and developers.

As will be seen shortly, one of the main challenges in developing an engaging learning experience is trying to find out what somebody is thinking. The use of artificial intelligence (A.I.) and complex knowledge-based systems (K.B.S.) could be particularly useful in achieving this, especially when used with conceptual and qualitative problems, i.e. "wordy" questions. However, adopting such technologies requires a completely new level of complexity to the methodology and necessary skills for achieving it, thus undermining the second goal – only using basic technology.

Furthermore, developing a deeply adaptive environment is technically extremely challenging, also requiring A.I. and K.B.S. An active environment with a low level of adaptability is still achievable, however, when working with common and more easily accessible technologies, as is the aim to prove by this thesis. (Recall Section 1.1.2 briefly reviewed the differences between adaptive and active learning.) Thus, achieving adaptability is not a necessary goal for this research and methodology. Working to satisfy the principles of active learning, however, is.

The methodology is interested in the crafting of the questions and environment for interactivity. Information technology (I.T.) is to be the enabling technology; the goal is not to advance I.T. but instead to advance an educational paradigm.

3.2 The methodology

This methodology is a collection of the tasks and rules necessary for building interactive elements and presenting conceptual material within a fully guided experience of learning through discovery. These methods and rules are grouped into four sets of design aspects or activities:

1. *the information design*
2. *the interaction design*
3. *the presentation design*
4. *the integration design*

A representation of how they relate is provided in figure 3.2.

The first three aspects parallel those adopted by Kristof, et al [16] in their book on design for interactivity. Here, however, their scope has been altered considerably to be more specific to our learning approach. Information design collects and organizes the material to be taught. Interaction design develops a means for engaging students with the information, and is concerned with the local control of their navigation. The Presentation design is concerned with the interface and modes of presentation.

Many of the tasks in the first three design aspects can be considered concurrently. A large amount of interdependence also exists between them, however. Thus, the last design aspect, the Integration design, is necessary to coordinate and control the various tasks and requirements for the other three. The result is an integrated process concerned with how the environment is actually executed and the students' navigation controlled globally.

The following subsections describe, in further detail, each of these design aspects, gradually working towards the final architecture of the methodology in Section 3.2.4.2. It is summarized in figure 3.6.
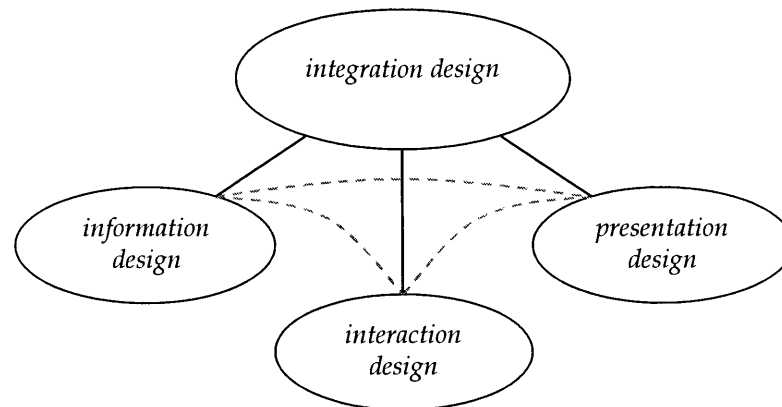
Figure 3.2   **The interrelationship between the four design aspects of the methodology**

3.2.1 The Information Design

Information design involves fashioning the material to be taught, identifying the desired engineering skills to be reinforced and establishing the correct teaching context.

The first step is to develop a full knowledge map of the subject material being taught. This map provides an outline for a library or series of modules that can be coordinated and developed. The knowledge maps for the engineering disciplines are very large. An ideal map is hierarchical, as indicated in figure 3.3. A more realistic representation is shown in figure 3.4. The hierarchy and structure degrade, particularly at the lower levels, due to the many interlinks and secondary relationships that exist between the individual domains and concepts. Therefore, when selecting a topic or "realm of knowledge" from this map to teach in a tutorial module, it is necessary to clearly define the topic's boundary and keep within it. An example of a potential selected topic and its domain is also shown on figure 3.4.

The benefit of these secondary relationships is the opportunity to develop context and connections between the new material and the student's own knowledge or observations from prior experiences. Furthermore, recalling that the approach of this methodology is to present the material in a linear narrative framework, the cross-references in the domain map can also present an appropriate and engaging discovery path for developing the necessary narrative thread.

legend
▓ : subject   ▒ : topic   ░ : concept   □ : sub-concept
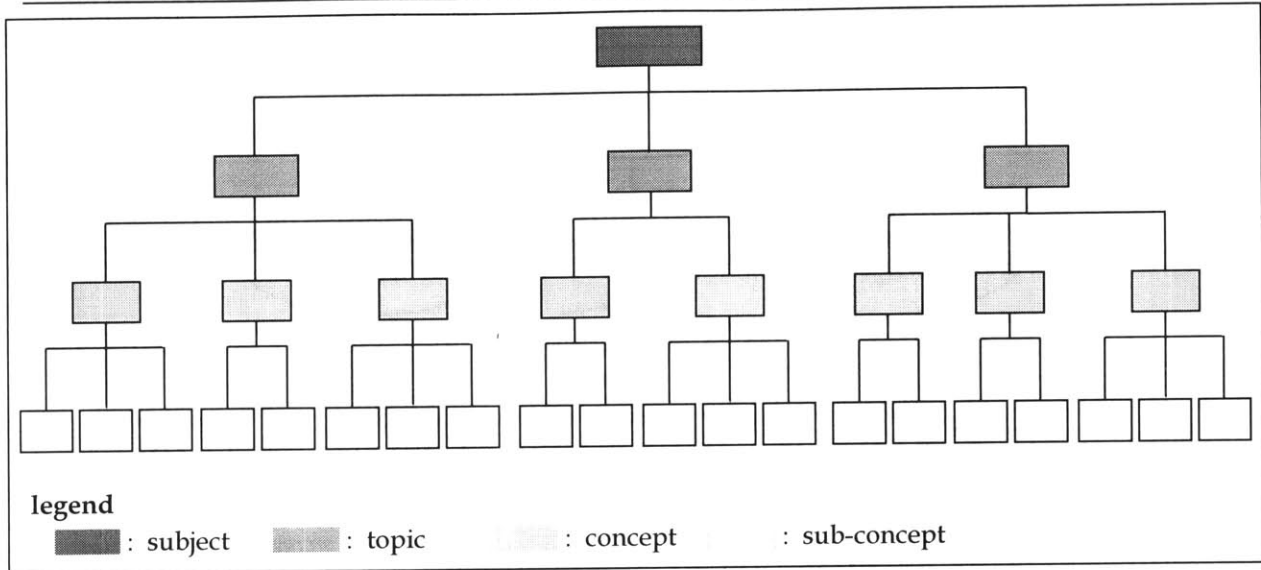
Figure 3.3   An ideal view of a knowledge map

legend
▓ : subject   ▒ : topic   ░ : concept   □ : sub-concept
------- : chosen knowledge domain   – · – · – : possible discovery path for topic
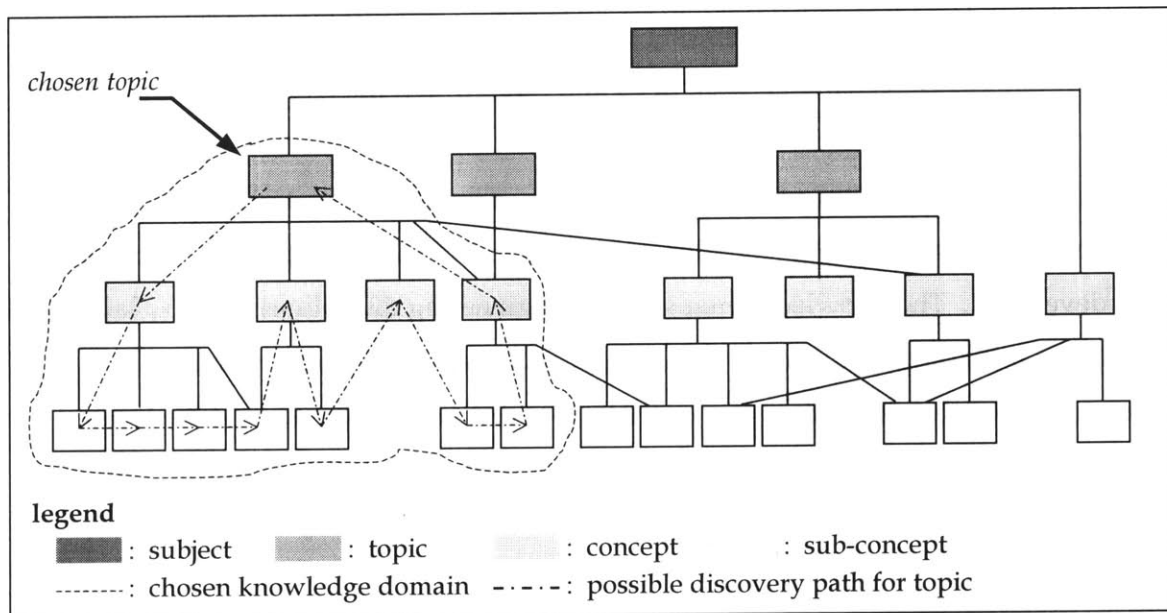
Figure 3.4   A more realistic view of a typical knowledge map with a chosen topic and its domain

A discovery path is a context to teach within and the path to follow to build the desired knowledge. A popular example is the use of "history", presenting a topic in the chronological order of its development provides a good narrative and makes the topic interesting, easier to follow and usually more relevant. For engineering, the most common approach is to begin with the basic concepts and phenomena of the topic and then build upon them, gradually increasing the complexity to reach the level of the

desired knowledge. Sometimes, to provide context and relevancy, the more complex goal is hinted at, at the beginning of the path.

The methodology uses this engineering model, but enriches it by capitalizing on the secondary relationships between the concepts within the chosen topic. This path then assists in providing the "bigger picture" and motivation for learning the topic. It is also important to keep this chosen path through the topic restrained, so as to maintain the students' focus and avoid confusion.

The steps involved in the information design process are:
1. define the topic, decide upon the audience and sketch the discovery path
2. finalize teaching context
3. identify engineering skills to reinforce
4. develop the framework of the material

In what follows, these steps are discussed in detail.

3.2.1.1 Step 1: define topic, decide upon audience and sketch discovery path

This key step determines the topic within the knowledge map to be taught. It sets the boundary previously discussed. More importantly, however, it identifies:
1. where the student lies in the body of knowledge prior to this learning experience,
2. where the student should be by the end of the experience, and
3. what is the discovery path that she should be taking to get there.

To answer the first of these three aspects, initial assumptions must be made of the learning audience and the prerequisite knowledge required of them before they should learn the chosen topic. This can be particularly challenging, especially when the students have a strong disparity in initial knowledge, or when catering to a variety of learning programs. Many institutions differ with respect to the order and emphasis of the areas of knowledge. In order to decide on what the students should know after completing the learning module, learning goals should be set.

Finally, for establishing the discovery path, the first step is to outline the subtopics, or steps, which the student will take, and sketch in how these are connected. This need only be a rough draft at this stage, as step 4 will build on this version and develop the module's own knowledge map.

3.2.1.2 Step 2: Finalize teaching context

Many of the issues for this step have actually already been decided on through the efforts of Step 1. It confirms the audience that will use the module and decides on how they will adopt it. For instance, will the students be of an introductory or advanced level? Will they use the tool in an individual one-on-one environment, in a group, or in the classroom?

As mentioned previously, the approach is modeled on the ideal of a tutor – a one-on-one experience targeted at an introductory level. Therefore, this methodology has been optimized for such a context. It is, however, still applicable for alternative contexts. The linear framework could definitely be opened up to be more web-like and open-ended, making it more appropriate for the web-like exploratory learning of more advanced students.

3.2.1.3 Step 3: Identify engineering skills to reinforce

As the initial motivation for this research is to improve the qualitative and conceptual engineering skills of students, it is obviously important to select a set of these skills to transfer through the module. The set of desired skills to choose from for each engineering discipline can be very large. Therefore, a single module will only be able to reinforce a few of these skills. A library of modules to cover the full range of desired skills is needed.

Many of the important skills lying in this range will already be apparent to the developer of the module; however, the full set should be established by examining practicing engineer's needs and considering the experts the students are to emulate. Simply doing pencil and paper tests on colleagues and students to observe what and

how they think can provide this valuable information. Covering the full set the skills in one single module is impossible; therefore, an achievable subset should be selected for the specific module being considered to focus on. For a series of modules, each one should consider a different set of skills. Then as a complete library, ideally they should cover the full set of skills. The skills that are selected for each module provide good suggestions when developing the simulations and style of the interactive problems to be covered in subsection 3.2.3.

3.2.1.4 Step 4: Develop the framework of the material

This step brings together the outcomes of the previous three steps, fully expanding the topic established in step 1. A topic covers a string or web of concepts; the framework or flowchart presents these concepts and their connections. To create this, one needs to fully identify the key concepts and subtopics along with any necessary explanatory material. Their order and connections will reflect the adopted linear discovery path.

As previously mentioned, one of the greatest challenges in the information design process is to keep the topic domain contained and the path through it focused. This is especially the case when one can easily digress into related design concepts and their interesting implications.

The tactic is to consider the issues of each subtopic and identify the knowledge and skills that the student will require to move on to the next one. Some additional secondary information may be necessary to achieve this. Furthermore, this secondary information enriches the context and/or provides interesting cross-references. Care must be taken, however, to always ensure relevancy.

Additionally, just as it is important to make assumptions about the student's prior knowledge, it is also important to consider her potential misconceptions. These are identified through observation and interaction with the prior audience during the development stages. With the misconceptions defined, the necessary additional subtopics can be provided where appropriate.

Lastly, a third layer of information exists in the framework. It is the complementary, optional material that will provide interesting "asides" or additional support for the student. Hyperlinks and popup windows are an ideal means for making this information optional but easily available. Providing the tertiary level of the knowledge hierarchy, this information is a powerful and easy way to:

    i.) enrich the learning experience further with more cross-references,

    ii.) briefly review material that was "assumed" to be already known by the student,

    iii.) refer to terms of a similar meaning that the student may be more familiar with from class,

    iv.) remind the student of a concept/finding from earlier in the module, and

    v.) clarify a point that may have been confusing, with more detailed explanations.

The development of the framework results in a fully detailed knowledge map and accompanying path. Three layers of information were found to the map:

1. the subtopics/concepts,
2. their necessary explanatory material, and
3. the "asides" and support material.

This map and path are used extensively in the other two design sections of the methodology – interaction and presentation. Therefore, characterizing these information layers early is important as they play a vital role in the rest of the module's development. In particular, each subtopic (level 1), along with the skills of step 3, will correspond to key interaction events in the module, as is discussed in Section 3.2.2. Furthermore, the layering of content and knowledge establishes the hierarchy for its presentation mode in the module, as will be explained in Section 3.2.3.

3.2.2 The Interaction Design

This stage in the design process examines the methods for achieving engaging the student with the information, adopting a pedagogical approach of learning through discovery. The goal is to train students to make choices, by confronting them with issues, asking them to reason through these issues and suggesting strategies to do so. Furthermore, the environment is to give them the security and safety to explore without

fear of failure. The approach chosen to achieve this goal in a fully guided experience is to design an interactive element for each subtopic or concept identified during the Information Design stage. Multiple-choice techniques and simulations are combined as the tools for interactivity, with supporting material provided to preempt the students' concerns and issues as best as possible.

3.2.2.1 The interaction process

For each concept or problem, the aim is to firstly engage the student with the phenomena being taught, through either experimentation with a simulation or observation of examples. At this step, the student sees no more than the necessary background context. This first introduction encourages the student to develop conclusions. Multiple-choice or multiple-answer problems then test these conclusions. Lastly, specific feedback is provided to the student's responses to these problems. The feedback then allows the concept to be reinforced and explains any incorrect responses with either further detailed demonstration or interaction.

Once the concept has been engaged with and the student has been encouraged to build her own correct intuitive ideas on it, the concept is then elaborated on through the secondary material to develop the linkages of the discovery path. This provides relevancy and enriches the learning context, which in turn, develops the groundwork for connecting the next concept in the knowledge map.

In providing this overview to the process, some of the key design issues quickly become apparent. In particular, to achieve success, the key is in posing effective problems. The problems must provide challenge and encourage reflective thought for the student; yet still have a set of potential answers to fit the multiple-choice model. The reason for this model's important adoption in the methodology is its use of simple standard technologies. Responding to written, qualitative answers from the student would require a much greater level of technology and artificial intelligence to apply the methodology. Yet, a well-designed multiple-choice problem can be equally effective in engaging the student reflectively whenever necessary. This methodology cannot show

how to actually write such an ideal problem but it does attempt to explain the key issues in creating one.

3.2.2.2 Tricks to designing the multiple-choice problems and their feedback

Ideally, each scripted choice in a problem, right or wrong, provides a clue as to what is the student's reasoning in making this choice and what is the appropriate and worthwhile feedback to deliver. The feedback is the vehicle for critique and reinforcement to the individual. Though challenging to achieve, it is important to make the feedback on the student's thought process, wherever possible. To decide upon what answer choices to offer, the student's potential thought processes, likely misconceptions and other interests need to be identified. An answer choice can be then designed to connect with one of these particular key misconceptions/ conceptions, and its corresponding feedback response can confront it and provide discussion on it

This leads into the other great challenge in the design of interactive components – controlling the level and amount of detail to provide in the feedback. A good explanation with interesting and relevant connections to the other knowledge is essential, but it must also remain succinct and clear.

3.2.2.3 Potential control paths through the interactions

For the more complex or important subtopics, a layering in this process of interaction with the phenomena and accompanying questions may be necessary, so as to lead the student through a progressively complex experience. Using continual testing and feedback on the student, her progress can be controlled dependent upon her demonstrated skill. Additionally, at the point of providing feedback for each choice there is the possibility for not only controlling progress but also sending the student on an alternative path, whether for extra training in a weak area or just through an alternative discovery path of the same material. Of course, these two control means when combined provide even more complexity. Some examples of the range of possible control paths are given in table 3.2. Further explanations of the ones that have been explored and implemented are given in Chapter 4.

Table 3.2   Possible control paths of increasing adaptability

type	control path	type of path
a	one	no feedback
b	one	same non-specific and general feedback and supporting information is provided to everyone
c	one	different feedback/explanations given specific to errors, but same amount of supporting information provided to everyone
d	alternate	same information and feedback provided as for type c order differs depending on interactions
e	one	both feedback and supporting information vary depend on errors and level of skill shown by student; exercises are the same for everyone, though
f	alternate	both exercises, supporting information, feedback and progress vary within each concept depending on level of skill shown by student
g	alternate	same as type f, but also actually vary how the next concept will be presented depending level of skill shown by student with current concept

increasing adaptability →

When deciding upon the appropriate control paths for the module, the issue of using simple technical skills again comes into play. This methodology focuses on the simple types b and c in table 3.2. The other types with their great complexity will require technology that is more advanced. Additionally, an important goal of the learning environment is for it to maintain a sense of freedom and exploration for the student. Too much hidden control could inhibit this and provide frustration. The following section, section 3.2.3, describes the methods of achieving the right balance of this through the presentation design.

3.2.3 The Presentation Design

Presentation or communication design implies the design of pictorial and textual information to achieve maximum access and understanding. Obviously, it is an extremely important issue when designing educational tools, which encourage strong user involvement and visualization. This section outlines the necessary presentation techniques and recommendations that this methodology has developed and/or adopted.

Some of the important presentation issues specific to the module have actually already appeared in the previous design aspects, i.e. the methods for creating interactivity in section 3.2.2. Recall that the three defined aspects are not independent, but are instead deeply interconnected with many of their design tasks requiring parallel consideration. Further explanation on how they work together is provided in section 3.2.4 – the Integration Design.

The first step in developing the presentation and the individual modes is to decide on the technology to develop the module. When making this decision an essential consideration is keeping this technology transparent. Hiding the technology, or at least putting it into the background, ensures focus is on the learning and reduces the student's possible inhibitions towards the computer. Current common types of technology for presenting information in the web format are HTML, JavaScript, ASP, Shockwave, Flash, Java or a combination of these with server-side databases.

Having decided on the technology to adopt, the next step is to work through the following two aspects of the presentation design:
1. the interface design
2. the methods for presenting material

Interface design is concerned with the design of the module's framework. This includes both its look and feel, but also how students navigate through it. The details of this are discussed in Section 3.2.3.2. The second aspect considers the techniques for presenting the content material effectively, such as deciding on the best mode to transfer the information and present the interactive experiences. This is discussed further in Section 3.2.3.3.

Before considering these aspects, however, a brief review is provided of the basic techniques and recommendations for *general communication design*.

3.2.3.1 Communication Design 101

With the goal of teaching the "engineer" and "educator" some of the basics of communication and graphic design – an important aspect in the design of computer learning tools, following is a review of many of the important issues. Two excellent references are "The Non-Designer's Web Book", by Williams et al [36] for advice and guidelines on graphic, text and web design, and "Interactivity by Design" by Kristof, et al [16] for web and interface issues.

The aim of graphic design is to communicate content and function effectively. This is achieved through a potentially very stimulating manner by arrangement of the visual field, guidance to the hand and eye within that field, and exploration through an appealing visual environment. The setting should ideally be unified, varied and balanced, which respectively imply coherence, interest and fulfillment.

The screen is a product of a variety of graphic elements, be they text, images or animations. Hence, an infinite array of their arrangements is possible, with the main parameters for each element being:

- location - within the screen and relative to the other elements,
- size - typesize and graphic size,
- style - typeface or artistic style,
- emphasis or visual weight - through density and line weight,
- texture,
- color,
- "whitespace" - with the amount and shape having strong visual impact.

Manipulating these characteristics are what create the graphical interfaces on computers with so much power. The assessment of their application and appropriateness is very objective, however. Therefore, some principles are required to guide the layperson in design.

Graphic Design Principles

There are four powerful principles of graphic design – the use of proximity, contrast, alignment and repetition. Each principle indicates possibilities for manipulating the parameters listed earlier in order to achieve a "good" design for communication. The nature of design, however, is to address multiple agenda. Therefore, it is important to remember that, not all of the principles can always be satisfied at once. The designer has to compromise at least occasionally.

Aiding organization by grouping related elements, *proximity* can imply relationship. Relationship between elements is a quality that students search for and are disturbed when it is not found. The use of proximity also simplifies the screen or view, by creating visual "blocks", and in turn forming interesting whitespace around them.

Contrast adds variety by allowing different elements to actually appear different, hence improving visual interest and interpretation of the screen. Using similarity, such as proximity, aids organization and allows contrast to imply the variance.

Assisting in creating an impression of unity, *alignment* of graphic elements forms visual connections between them. This assists visual organization by directing the eye. The role of alignment is also important for both text justification and the arrangement of larger elements.

Finally, *repetition* provides unity and consistency to a screen by repeating elements. Creative use of it can also spark visual interest. An important characteristic of repetition, is that it denotes organization, and hence, care should be taken not to use with it unrelated elements.

Table 3.3 summarizes the strategies for applying these four graphic principles.

Table 3.3   Strategies for Applying the Graphic Design Principles

Principle:	Proximity	Contrast	Alignment	Repetition
Strategy:	▪ aim for 3-5 points for the eye to rest upon per screen, ▪ avoid equal spacing of disparate things, ▪ vary spacing to indicate closeness, and follow the structure, ▪ create interesting spaces, avoiding centrality.	▪ use with confidence, making obvious contrasts, ▪ achieve by using all the parameters, i.e. size, style, color, etc, ▪ use strong elements sparingly, i.e. only for important features, ▪ create focal points and eliminate clutter.	▪ create an explicit grid, ▪ avoid mixed text alignments, ▪ avoid using center alignment, unless using a formal or stable effect, ▪ avoid aligning at a page edge – provide margins.	▪ emphasize consistent elements using bullets, typefaces, colors, icons, etc, ▪ consider adding repetitive elements, however excess should be avoided – simple and clean is best.

3.2.3.2 Interface Design

Interface design is an integral part of the module's design; it has implications on the page layout and the "program" structure and navigation through it. The three major principles of interface design are those of User Correctness, Least Astonishment, and User Centeredness. The first one is the simplest but also the most important; no matter what a designer may think the user is always right. Due to this, good designs have in-process testing, as will be discussed briefly in section 3.2.4.

The second principle – *the principle of least astonishment* – is concerned with the actions and results of the module always being what the student anticipates. Otherwise, the student can end up frustrated and confused. To achieve predictability, the five qualities to express are simplicity, clarity, completeness, consistency and robustness:

Reflect *simplicity* throughout the whole software: its structure, layout, and navigation and task controls. The format should be apparent and easily comprehensible.

Navigation decisions at any point are best if kept limited and straightforward, and the screen controls to achieve these movements and other tasks should be uncomplicated.

The role of a control should always be immediately clear to students. Achieve *clarity* through such tricks as making the most important controls prominent and using metaphors, through graphics, and the like. There are many standards, such as scroll bars and arrows, to exploit wherever possible to communicate a control's purpose quickly and concisely.

On any one screen of the module or environment, there should always be adequate control to enable the student to accomplish her minimum set of desirable tasks. This reflects the *completeness* of the program – achieving what the student expects and needs it to do, and hopefully most of what she would like it to do, too. Providing a minimum set of explicit controls to exit, go "back" or to the contents are good methods of satisfying this requirement.

Consistency in all aspects of the module's appearance and function improves efficiency and reduces frustration for the student. If a set of elements is similar then ideally they should look and work in the same manner, however if they are not similar, then they should work differently. This goal can be achieved by using appearance, placement and operation to both support similarities in functions and distinguish between dissimilarities in them.

Normal human behavior is to make mistakes. Anticipating student actions and preventing accidents should design for this error. One of the most effective measures for *robustness* is constraining student's input, by rejecting empty input or using popup menus. Be alert also to unintentional navigation within the program – such movements that could take the student to surprising locations. This can be a particular problem with the web-like paths possible with the module and environment. The best approach to assess robustness, however, is to test the package on novices from the target

audience. As has already been touched on and will be discussed further in Section 3.2.4, an evaluation process is an essential component to any good design,.

By considering these four goals of simplicity, completeness, consistency and robustness and their roles in achieving a situation of least astonishment for the student, has demonstrated the importance of the principle. Diligent application of it will provide a friendly and worthwhile learning environment for the student.

Finally, the *principle of user-centeredness*; the student should always be placed at the center of the module. The three main aspects of this centeredness are control, responsivity and forgiveness. Students always like to be in *control* of the program, so the design should strive to give them this or at least the appearance of it, if hidden complex control paths are used, such as those referred to at the end of section 3.2.2. Ideally, the *response* of a student's actions is immediate, and if this unfortunately is not achievable then the program should be keeping the student informed. Without such a response or advice, the learning experience from the program is greatly reduced, and possibly even totally. *Forgiveness* relates to the "robustness" quality defined in the previous principle. As stated above, it is a fair assumption that students will make mistakes; hence, a good program should provide easy means to correct them, wherever possible.

Describing the design issues dictated by the three principles of interface design highlights many of the important techniques to apply in the module design and educational software design in general. A few more details are still to be mentioned, however, that are particular to the methodology and its approach only.

Recall that the approach weaves the *Tutorial Cycle* and the other elements of the primary learning theories in with the components of multimedia and simulation, to present the material in a narrative form. The interface and framework for the content material to sit in is to be a relatively traditional layout with two main regions – one for text and the

other for graphics/simulations. The merging of the interactivity elements with text is seamless.

For the navigation methods, an additional recommendation is required for the interactive elements. To encourage engagement yet avoid frustration, for a given interactive problem the student is given a set number of attempts, after which point she is given the option to try again or be given the answer. In accordance with giving control to the students, the choice is up to them and they are always able to continue forward after a minimum level of interaction. This recommendation is only applicable to the interactive control paths defined for this module in section 3.2.2; however, it is advisable that the idea is also adopted when more complex control paths are used.

Furthermore, even with the interface's apparent appearance of choice, to ensure the linear narrative flow of the module, the navigation should actually be restricted to allow only one option for the student if she wishes to advance further into the module.

3.2.3.3 Modes of Representation

This aspect of the presentation design involves the techniques for actually representing the content material to be placed within the framework of the interface design from Subsection 3.2.3.2. As already alluded to in this previous subsection, multiple representations of the information are used throughout, i.e. text, photographs, symbols, diagrams and animations. Capitalizing on a rich representation provides a more interesting experience and can cater for a greater breadth of learning styles. When designing the interface, ideally it should have at least two distinct regions – a graphical one and a text one.

Recall that the knowledge map developed during the information design in Section 3.2.1 reveals a hierarchy of three layers of information (the subtopics/concepts, the explanatory material and the support material). Each level is presented by a different mode. The subtopics and concepts are what the student is to learn, ideally through discovery with the interactive elements. The necessary images and simulations for this

will be displayed in the graphical region of the screen, while the text region will present any guidance or descriptions to accompany the interactive elements. The second level of information, the explanatory, background and interconnecting material, will also use the graphical and text regions.

The third level of information, the "asides" are presented through hyperlinks and popup windows. Clicking on a hyperlinked term will pop up a box of text and/or graphic that expands further on the term. This methodology recommends making the tertiary information available to all students doing the module. Members from the full spectrum of the target audience will find the information useful, be it for differing reasons. Of course, other developers may take a different approach, especially if using more complex control paths.

Emulating an informal tutor, the text is written with a relaxed and conversational tone. An important issue in developing the text or script is deciding upon the accepted terminology to be used. Instructors have their own slight variations and preferences for many of the standard engineering terms, i.e. a fixed connection is also known as both a moment connection and a rigid connection. Therefore, when writing the text, these variations must be acknowledged, preferably by referring to them all, clarifying which one will be used and then being consistent. Using an "aside" to discuss the alternative terms is a convenient way of achieving this.

The use of animations and other forms of visual representation can be extremely powerful; "a picture can tell a thousand words". When building the module, therefore, use graphical elements throughout, aiming to have some form of accompanying graphic for every section of text. Using images of real examples is particularly effective; real-life examples are an oft-neglected component of current engineering education. Graphics are also particularly powerful in the interactive elements due to their ability to demonstrate the phenomena and provide a feedback mechanism for the student to do self-judgment.

Section 3.2.2 introduced some of the tricks to presenting the interactive elements in the module already. The summary of these steps is:

1. present any necessary prerequisite information,
2. engage student with phenomena usually through simulation exercise,
3. provide feedback responses specific to simulation interaction,
4. query student on her observations,
5. provide further informative feedback, and lastly,
6. summarize findings and reinforce knowledge just gained.

Each interactive element will adopt each step to a varying degree of detail, i.e. some may not use an advanced simulation exercise but instead just visual examples to be questioned on. All elements, however, contain all steps to at least some extent for successful learning and engagement with the concept. A few optional steps also exist. Sometimes between steps 1 and 2 a demonstration is required to, firstly, set the expectations and lead the student towards the exercise's desired outcome, and secondly, to remove the "goofy" answers/interactions as possible options. Thus, the student's experience is used more efficiently.

The query/feedback steps (steps 4 and 5) are iterative as the student may make multiple attempts (typically two). After each attempt, if incorrect she is advised of the level of inaccuracy and an optional hint is made available. Typically, techniques for providing the hints are a "hint" button providing a popup window or a hyperlink on a related term providing useful and related side material. Ideally, these hints are process oriented, not just content oriented. Additionally, steps 4 and 5 may be used multiple times as a string of follow-up problems that test the student on scenarios she may not have stumbled on during the simulation exercise. Through the example of these problems, however, there may be some powerful demonstrations of the concept and now the opportunity is available to point this out to the student more easily. Equally, examining counter examples of "wrong answers" can be valuable for the learning process.

The module always presents the embedded simulations in a qualitative format. All numerical and analytical representations are hidden from the student; instead, symbols and terms are used with drag and drop or popup menu capabilities. Students still learn to analyze and problem solve but purely in a conceptual manner. The steps for the simulations, steps 2 and 3, may also be iterative to encourage a sense of play and allow the student to engage with simulation as much as she likes. Furthermore, the feedback given on the student's interaction (step 3) is typically visual only, to allow self-judgment. Just as with steps 4 and 5 for the problems, hints are optional and are provided to prompt the problem solving. Similarly, the correct answer and conclusions are not given until the student has engaged in the simulation for at least a minimum amount of effort.

All of these techniques and guidelines cover the design of the components of the module and its framework. These are adopted to varying degrees in the prototype module that demonstrates this methodology. This prototype is presented in chapter 4. How to best piece these components together though has not yet been covered. What is an effective order of presentation? The next section answers this question as it brings together the work of the sections 3.2.1 to 3.2.3 to develop a complete design of a seamless and engaging learning experience.

3.2.4 The Integration Design

There are two aspects to the Integration design; firstly, how are the components from the three different design aspects integrated to produce a cohesive learning experience? Secondly, how are the steps of the three different design aspects integrated into a clear, stepwise process?

3.2.4.1 Integrating the design components to present them in a fluid format

Developing a storyboard to define what happens on every screen helps to achieve this fluid integration. A storyboard presents the information and actions that occur on each screen of the module; hence, by putting these screens together a walkthrough of the module is achieved. The framework of the knowledge map and its discovery path

created as a part of the Information Design reveal the narrative sequence. This just needs to be expanded on to indicate the material to be presented and its order and mode of presentation, as decided during the Presentation Design. Adopting the linear interactive control path between concepts, from Section 3.2.2.3, figure 3.5 shows the expected sequence.

The introduction presents the topic, the learning goals and expectations, as well as setting up the learning framework for the student. Motivation and relevancy are provided by touching on where the topic fits into the larger curriculum map. The first concept is then introduced. The subsequent concepts build upon this first one, with each, ideally, providing the prerequisite understanding for the next. The interaction format presented in the Interaction and Presentation design are used for this process. Additional steps in the development of the storyboard are the drafting a script with the text from the Information design and fine-tuning the knowledge hierarchy and presentation modes developed in the Information and Presentation design.

Once the storyboard is built, the design can be implemented and the prototype built. Only one last crucial step remains; members of the target audience must evaluate the module to ensure it performs in the manner expected. This includes testing the interface and presentation modes, as mentioned in Section 3.2.3.2, as well as the format and order of presentation of the material. Are the expectations and explanations for using the
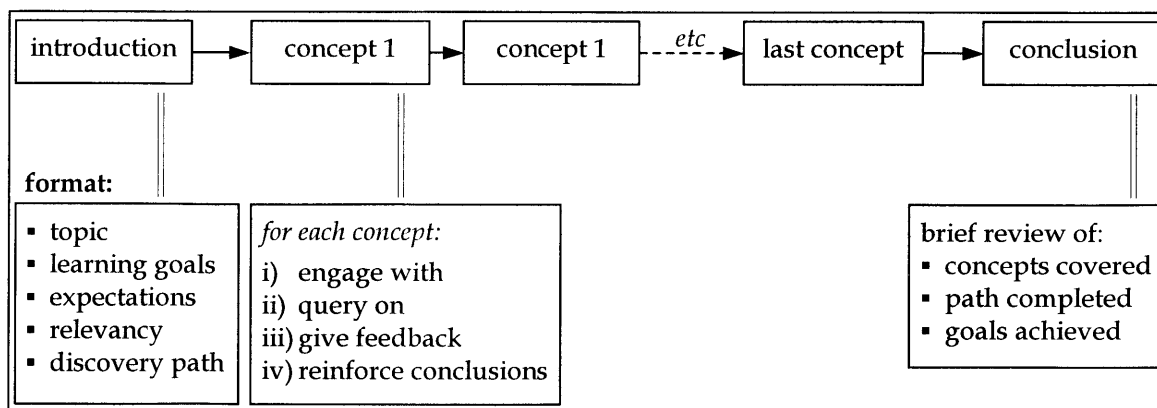
Figure 3.5   **Sequence and format for presenting the components within the module**

interactive elements adequate? Are the students interacting with the exercises as expected? Are they getting out of it what was intended? Is the feedback helpful and on target? To answer these questions, students should be observed using the module, surveyed or asked through discussion what are their thoughts on the experience. Lastly, the module should then be revised to incorporate the results of the evaluation. Thus, this is obviously an iterative and ongoing process during the prototype's development. The effort pays off however with a resulting product that is worthwhile and effective. Chapter 5 discusses evaluating the modules in detail.

3.2.4.2 Combining the design steps into a single representation of the process

As was seen in the description of the three design aspects, their tasks are a combination of sequential and concurrent, being sometimes parallel and often interrelated. For instance, a sequential example is knowing the technology to be adopted during the presentation design stage will help to know what interactive exercises designed in the Interaction design are feasible. Thus, how the design aspects and their tasks are blended to work as a whole is best clarified through the flowchart in figure 3.6. Some of the resulting design steps display the iterative nature of the process.

This resulting flowchart is the final architecture of the methodology for building an active computer-aided tutorial to teach concepts, as it summarizes the design steps, their order of execution and their interplay. The details and techniques for each step are available by simply referring back to their descriptions in the sections on each original design category.
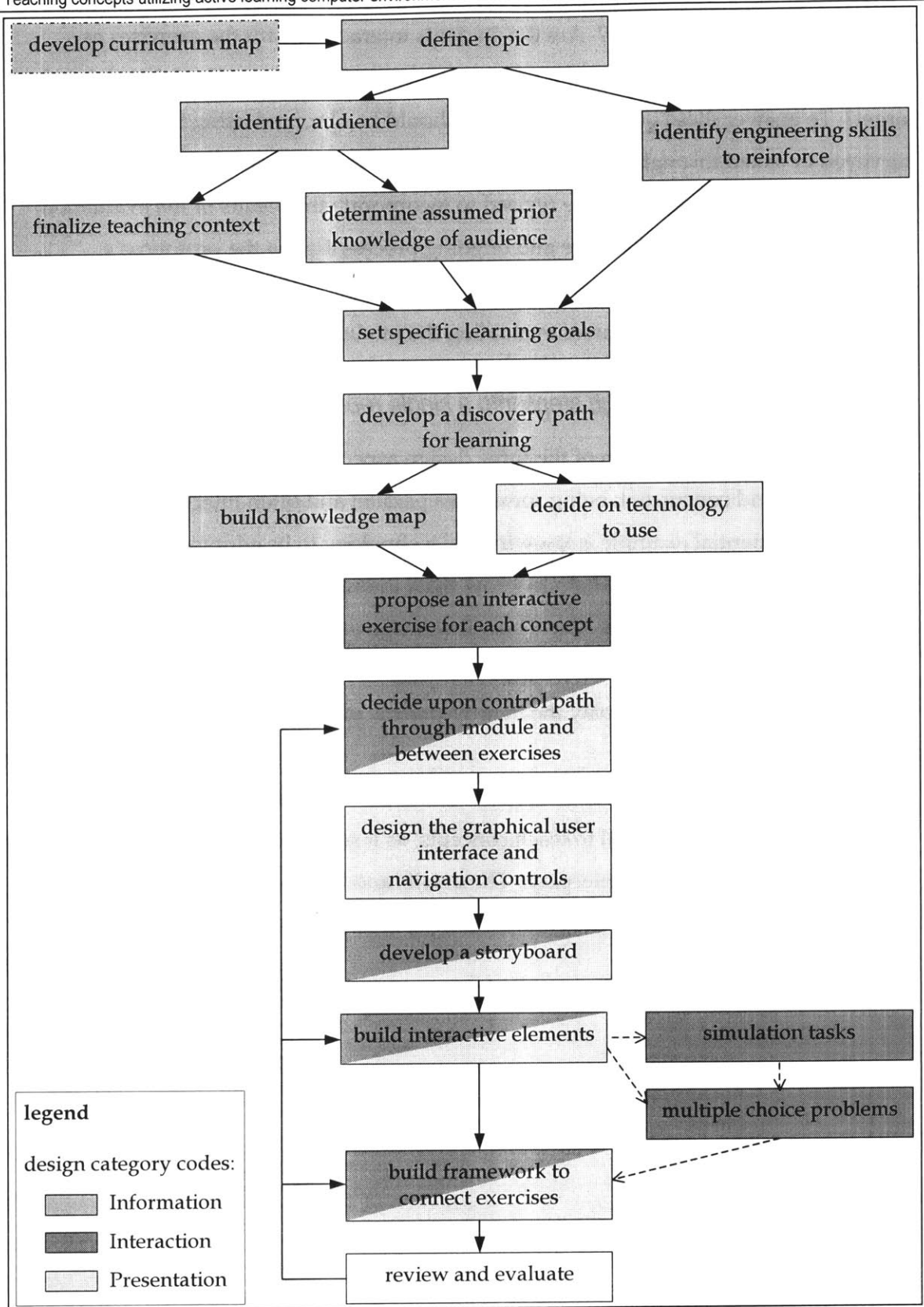
Figure 3.6   The flowchart representation of the methodology

3.3 Conclusion

This chapter presents a methodology for building an active computer-aided tutorial, beginning with the basic design components and working towards a final integrated process. Working to satisfy the goals set out in Section 3.1 produced an experience that encourages critical and reflective thought and provides challenging and experiential opportunities for learning concepts. All using common and transparent technologies.

All of the pedagogical goals were achieved. The *Tutorial Cycle*, in particular, has a strong influence on the methodology and module. For instance, the format of teaching each concept with an interactive experience clearly reflects the *Cycle* (refer back to table 3.1 to view its components). The interactive exercise and its initial explanations engage the student in the concept, presenting information related to the goal (learning the concept) and eliciting the student's action towards the concept. Her action is then evaluated and feedback is provided. Sometimes, follow-up multiple-choice problems are adopted to assure these steps of the *Cycle*, assessing and feedback. Finally, the navigation of the student through the experience provides the strategic guidance and management and both the supporting contextual material and experiential nature of the environment provide the motivation for the student.

The best understanding of how to achieve these learning experiences through following the methodology is gained by implementing it. Chapter 4 provides this implementation with a description of a module and its design process that was developed within the context of structural behavior.

Chapter 4

Implementing the methodology

Earlier efforts were made during this research to solve the problems discussed in Chapter 2. Two of these modules were presented in the author's Master's thesis [29], the "Seeing Load Paths" slideshow and the "Point Loads on a Simply Supported Beam" exercise. Although simplistic, this initial work began to explore some of the basic ideas for engaging students with physical phenomena and the concepts of structural behavior. Modules of greater complexity followed that investigated and experimented further with the communication and interactive techniques, taking them to a more sophisticated level. All of this work led to the final evolution and culmination of the methodology presented in Chapter 2 and an accompanying prototype. This chapter describes the prototype and how the methodology was implemented.

The prototype module was developed within the context of structural behavior. As noted earlier, the methodology is also applicable to many engineering topics of a conceptual and qualitative nature. The topic chosen for the module was *"rigid body stability"*. More on what this topic is and why it was chosen is provided shortly in Section 4.1.2.

Section 4.2 discusses how a library of these modules could be developed and some initial attempts at achieving this library are presented.

4.1 Building the prototype

This section steps through the development of the final prototype using the methodology outlined by the final flowchart in figure 3.5. Each subsection describes a single step, with its accompanying techniques and design influences. The prototype module provides the best means for demonstrating many of the ideas and techniques of the methodology.

The various aspects of the module are presented as screenshots. Unfortunately, a lot of the interactivity and animated nature of the environment is lost in these single moments. A CDrom containing the module is included with this thesis. Additionally as there are so many screenshots used for demonstration in this chapter, they are all shown together in Appendix B, instead of within the text.

Furthermore, when discussing the implementation process in the following subsection it appears to be very linear with each stage following on from the next. In actual fact, the procedure was quite iterative.

4.1.1 Develop curriculum knowledge map

Before a single module is developed, it is necessary to develop a knowledge map or syllabus of the subject material being taught. As already mentioned, the original area of interest is Structural Engineering and behavior. A fully developed knowledge map for this is in Appendix A. Professor J. J. Connor, made the initial developments of this map. When creating this map, recall that a hierarchy develops. For this case, the concepts in the third level typically have the desirable magnitude and scope for being candidates for a module topic.

4.1.2 Define topic

Once the map is developed the potential module topics become clear. Examining the knowledge map in Appendix A, good qualitative examples of varying complexity that would make good modules are Nature of Materials, Nature of Environment, Simple Frames and Linear vs. Nonlinear Systems. Some of the topics may be combined into one module or even broken down into smaller separate modules. Such decisions, of course, are all a part of the design process. Some overlap between the modules, however, is also acceptable. Creating the right balance is the challenge. This idea of developing a library of modules is discussed further in Section 4.2. Alternatively, the designer, of course, may already have a topic in mind before developing a knowledge map. However, it is still always advisable to see where this topic and its module will fit into a library. As will be observed in chapter 5, the modules are most effective when presented as one of a series.

For the development of the prototype module, a topic was desired that needed little prerequisite knowledge from the students. This would ease the module's evaluation process, allowing greater flexibility with students from a variety of schools and course levels. Chapter 5 covers the evaluation process in full detail. Ensuring that almost any elementary statics student was capable of competently engaging with the module and completing the evaluation material was important. Therefore, the topic chosen for the prototype tutorial was *"rigid body stability"*.

Rigid body stability encompasses the stability of a structure, be it a single beam or an assembly of elements, such as a frame. It does not include the more complex issues of deformation, requiring second order analysis with column buckling and snap-through buckling. The topic is an extremely relevant yet elementary concept that teaches students to always provide adequate support to a structure. Surprisingly, this is something that students often take a while to pick up, particularly as it is not usually taught explicitly in class, mainly due to it seeming so elementary. From stability, however, the students can better understand determinacy, indeterminacy, redundancy

and support types, among other things. More on the key issues and concepts for teaching stability are included in Section 4.1.9.

4.1.3 Identify audience

A simple step, identifying the audience asks, "Who will be using the module?" This methodology is particularly appropriate for the introductory topic chosen. Therefore, students in their first structural analysis or statics class are the target audience of the prototype. They could be either Civil Engineering or Architecture students. Although the potential is available for other users, the module is directed towards the aforementioned audience.

4.1.4 Determine the assumed prior knowledge of the audience

An important part of knowing the target audience is knowing what they should know before commencing the module – what is the required prerequisite knowledge? To answer this, it is best to examine again the larger knowledge map of Appendix A, and see where the module's topic fits in. Recall that the topic of rigid body stability was chosen as it sits early on in the map and requires very little prior knowledge. All that is necessary is:

- an elementary understanding of vectors, forces and loads,
- an initial introduction to stability, i.e. familiarity with the equations of equilibrium for at least two dimensions, and
- ideally, basic experience in how to calculate the reactions of a determinate beam.

Lastly, it is also important to know what the potential audience's misconceptions with this topic may be. This will help in ensuring the topic's knowledge map and discovery path developed in the future design steps will be adequate. To achieve this, observe and question students on the topic. Typically, however, many of these misconceptions will be apparent to the developer through her interaction with the students during teaching, etc. Most of the assumptions used in this implementation were based on such experiences.

4.1.5 Finalize teaching context

With the audience decided upon, the rest of the expected teaching context needs to be established. The prototype module and the others in the "library" are envisaged as being assigned by the instructor as homework. The students would then use them alone, when at home or in a school computer lab, where they can work unassisted and at their own pace. The material covered complements the more analytical material taught in the classroom; it does not replace it.

Each module would ideally take the student anywhere between forty to fifty minutes to complete. For completeness of the student's learning experience and evaluation purposes with the prototype module, the full scope of the chosen topic is to be covered. Therefore, this module is slightly longer than ideal. It is designed to takes a student approximately an hour to complete.

To aid in its accessibility and ease of use, the module is run in a web environment, available over the Internet. An important consideration of the teaching context within this environment is the student's movements through it and her access to the information in the module. Must the student go through the whole module from start to finish or will she be able to jump ahead and skip sections by using a contents menu? Will she be able to cross-connect to other modules in the library or even to the World Wide Web (WWW) or will the student be contained fully within the module in question? Obviously, the answers to these questions will dramatically affect the flow of the narrative path and style to be developed.

For the prototype module, the student's movements are fully restricted within the module. She is required to go through the whole module from start to finish; there is no possibility to fast-forward. This decision was due mainly to the desire to ensure the student is engaged with all of the material, so that her learning experiences from it can be evaluated as effectively as possible for research purposes. Nevertheless, controlling the student's movements and restricting them with the module is recommended in order to maintain both a realistic conversational style and the student's focus. Allowing

her to jump ahead is still potentially a desirable feature, but perhaps can be provided once the student has been through it all in the desired controlled manner. When she returns a second time for review or reference, a contents menu could be available to allow her to skip certain sections and jump ahead to the sections of interest. Further discussion on such control alternatives and its implications is provided in Sections 4.1.12 and 4.2.

4.1.6 Identify engineering skills to reinforce

In Chapter 2, a set of important skills was identified as lacking in many newly graduating engineers. A great part of the motivation for this research came from the existence of this list. Therefore, deciding on the engineering skills to be reinforced by the module is obviously a very important step in the design process. The best approach is to identify a full set of skills, much like this aforementioned one, that is to be reinforced by the complete library of modules. Then select a smaller and achievable subset from it that the module being designed may focus on.

Furthermore, these selected skills often provide good suggestions when deciding on the types of simulations and the style of the interactive problems to use. When identifying the skills, it is important to select skills that are broad, essential aspects of being a good engineer. They are not to be just knowledge. This can be challenging to obtain. The complete list of skills and abilities, as previously mentioned, was developed by exactly these means in Chapter 2. For convenience, the essential skills are repeated here in table 4.1. As referenced in Chapter 2, it was obtained by reading current literature on the state of engineering education, consulting a few practicing engineers and through the author's own observations.

The subset chosen for the prototype is:
- differentiate between a structure and a mechanism
- achieve a conceptual knowledge of geometric compatibility
- follow and identify load paths

**Table 4.1 The skills required as apart of the desired abilities of
a structural engineer**

- understand and predict changes to a model
- differentiate between a structure and a mechanism, applying the requirements of both equilibrium and stability
- achieve a conceptual knowledge of geometric compatibility
- follow and identify load paths
- identify the various modes (tension, compression, bending, shear) by which the load is carried
- predict not just the deflected shape, but actually thoughtfully considering how the structure - be it beam, truss or frame - deforms under load
- predict the bending moment and shear force diagrams
- predict reactions for any type of statically determinate structure
- establish the member forces for a statically determinate truss
- offer creative design solutions
- communicate this information through sketches

4.1.7 Set specific learning goals

Following directly on from the previous step is the establishment of the learning goals specific to the module. Obviously, reinforcing the engineering skills just identified are some of them. Also included are at one end of the scale, the teaching of skills specific to knowing the topic of the module and at the other end, the grander goals of the teaching approach, as discussed in Section 3.1.1.

This hierarchy in the learning goals is seen in the list that was developed for the prototype. The learning goals for the student are as follows:

1. differentiate between a structure and a mechanism
2. achieve a conceptual knowledge of geometric compatibility
3. follow and identify load paths
4. understand stability
5. able to make a rigid body stable
6. apply equilibrium and stability requirements
7. identify determinate and indeterminate structures
8. recognize redundancy
9. understand the effect of different types of connections
10. gain enhancement to classroom knowledge by focusing on behavior
11. see a connection between real life and the analytical representation
12. gain a sense of the bigger picture

The first three goals are the desired engineering skills to be internalized by the student. The next six goals are the skills specific to understanding rigid body stability. The final three goals are the broader goals of this teaching approach for conceptual learning that improve upon the student's classroom work, and transfer a sense of how engineering, structures and the design process operates.

4.1.8 Develop a discovery path for learning

Next, the plan of attack on how to teach the material needs to be developed. What order for the content will ensure its effective and clear presentation, while demonstrating its relevancy and interest? In answering this question at this stage, only a rough outline needs to be provided for the discovery path. However, this outline provides the inspiration and style for the future stages.

The linear approach of the tutorial requires a narrative and conversational format. As stated in Section 3.2.1, using an historical context to present material chronologically suits this approach well, providing a story that allows a variety of interesting asides for

real-world interest and enrichment. A more common and sensible approach for teaching the engineering processes, however, is the use of "divide and conquer". Working from the simple to the complex, an engineering concept can be developed and built upon. This form of discovery path is particularly good for the module and others in the library as it demonstrates a common engineering practice – breaking down a problem into smaller easier components – yet it also allows the opportunity for internalization of the knowledge with the progressive interaction and repetition of ideas. The module uses exactly this process with a discovery path that begins with learning how to stabilize a single body or beam and then works up to an assembly of bodies, along the way covering the issue of how supports are provided for this stability and what they actually look like.

4.1.9 Build knowledge map

The topic and the larger curriculum map in which it fits were both defined at the first stages of creating the module. Next, a portion of this map needs to be chosen for the module to cover. This more specific, smaller knowledge map establishes a framework, defining the concepts to be taught and the paths connecting them. For the topic of rigid body stability, the concepts to be taught are:

- rigid body motion; including the terms translation and rotation
- stability of a rigid body
- determinate
- indeterminate
- redundancy
- a recap on loading types
- support types: pin, roller, moment restraint, etc
- assemblies
- mechanisms
- lines of action

The knowledge map provides an avenue for fitting this range of concepts together under the umbrella of rigid body stability. In making the connections, the discovery

path developed in the previous step is used, which begins at the basics and gradually becomes more complex. Furthermore, at each concept, its necessary knowledge and issues are considered. What are its goals, why has it been included and how will knowing it assist in working towards the more complex and desired result of testing a basic assembly structure for stability?

The resulting map is in figure 4.1. It is the framework for constructing the rest of the module. The map also begins to reveal the hierarchy used to develop the interactive
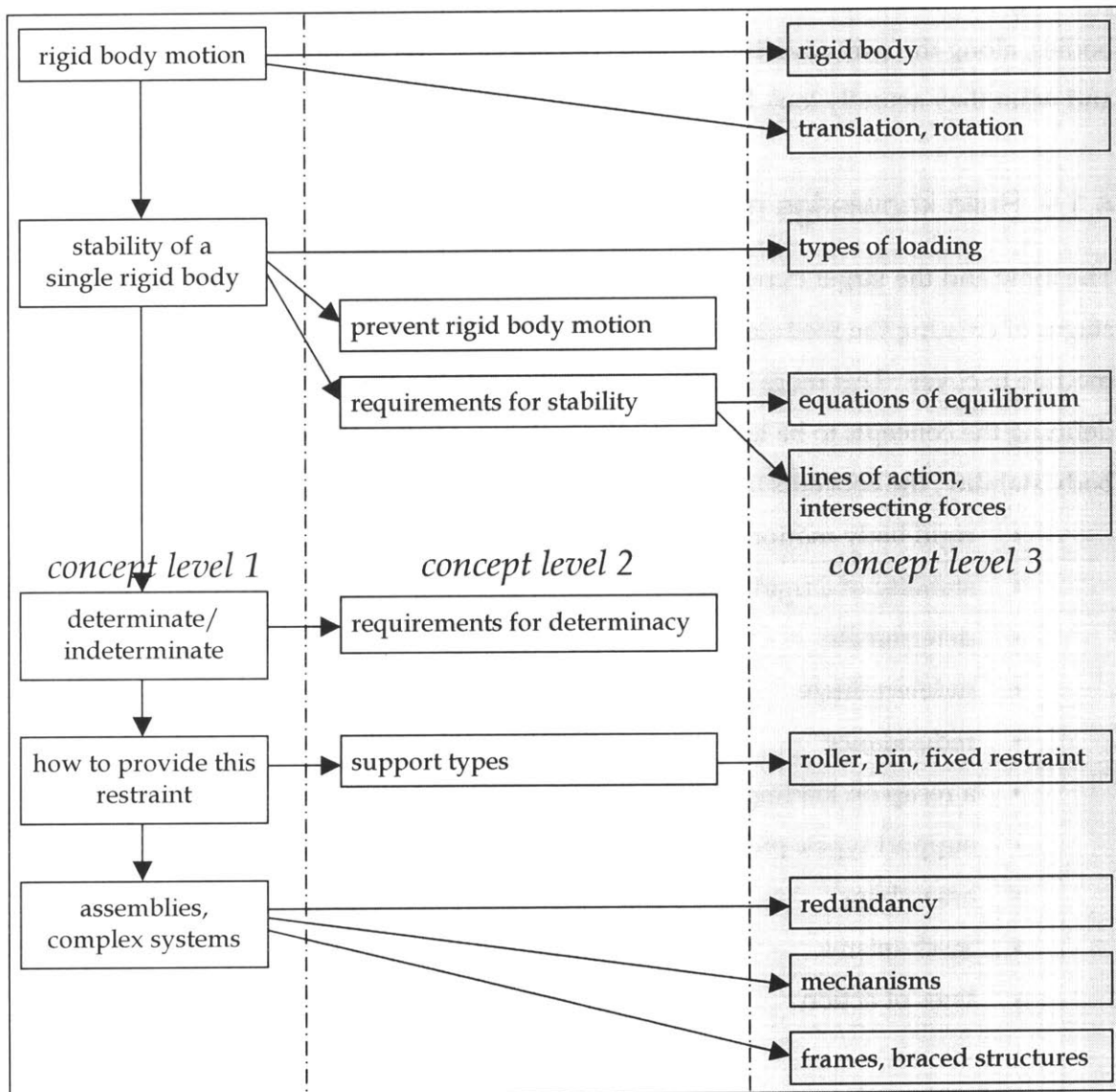
Figure 4.1 **The knowledge map specific to *"Rigid Body Stability"***

components, asides, etc. For example, considering the stability of a single rigid body – to understand what makes a body stable, it is necessary to first know the types of loadings that the body undergo and, second, to know what could cause instability (rigid body motion). Working through these steps, the requirements of stability can then be surmised. Additionally, the necessary connections can be made with the students' prior knowledge (equations of equilibrium) or supporting concepts (lines of action).

Two other important aspects need to be covered when developing this map: defining the terminology and deciding what concepts will not be covered. To ensure consistency it is essential that the concept names and terms are set early and do not change further on in the module. Often there are differences in the terms used by instructors and schools. These should be recognized not only in the planning but in the text of the module itself; alternate forms can be presented as "asides" via hyperlinks.

Deciding on what not to include in the knowledge map can be very challenging. Knowing when to draw the line with conceptual and qualitative topics is not easy, especially as discussed in step 4 of Section 3.2.1.4. For instance, the concepts were not included but could have easily fit were:

- center of gravity
- degrees of freedom
- how a "point" can represent a joint/support location
- stability issues in all three dimensions

Some of these concepts were actually touched on slightly in the module, although they were not developed. The reason for not choosing these concepts was that they were seen as unnecessary for supporting the discovery path and previous design choices. If included, they may have clouded the issue and caused an information overload. Digress too far off the topic of stability and the module quickly becomes too long! Not all of the cuts made were necessarily apparent at this stage; some were actually carried out during future stages as an iteration in the design. The list above simply reflects a summary of the final outcome.

4.1.10 Decide on technology to use

Once the types of concepts to be taught have been decided upon, some preliminary notion on how to teach them is sure to be apparent. Initial simulation approaches may also work to spark these ideas. Therefore, with the teaching context defined in Section 4.1.5 and the learning goals of the approach in mind, the computer technology to use to achieve these is now chosen.

Macromedia's Shockwave was adopted to develop the module, as it best met the demands for building a tutorial environment with the desired aforementioned qualities. Shockwave or Director, the program within which the Shockwave movies are developed, uses graphics, sound, animation, text, and video to create interactive multimedia experiences quickly and easily. Once compiled, the platform independent Shockwave movies are embedded in a web page and are then accessible through any web browser. A plugin may be necessary for the browser, but this can easily be downloaded and installed by the user.

Director is ideal for developing the module as it rapidly creates a page-by-page environment with straightforward navigation. The interface design is fully customizable and text, graphics and animations are very simple to add. Lingo, Director's object-oriented programming and scripting language, allows control and manipulation of these elements to add powerful interactivity and data tracking, as well as script-driven animations and effects. Therefore, Director is very flexible, allowing personalized narration, specific feedback and easy and optional digressions for further explanation and demonstration. Furthermore, it is possible for the technology to remain transparent.

A popular alternative approach for developing learning tools is Sun's Java applets. They too are embedded within web pages. Providing the supporting narrative text and graphics and particularly the aside comments, however, is much more laborious in Java. The web page could be used to provide this aspect of the content, but communicating

between the web page and embedded applet becomes a challenge. Hence, the fluidity of the interface and personal feedback could be lost.

Java, however, does have one advantage over Shockwave for presenting engineering concepts. Java handles complex mathematical problems and analysis more effectively and, consequently tends to be very popular for many educational simulation tools. The conceptual and analytical issues of the prototype module's topic, however, are quite straightforward and can be effortlessly handled by the simple programming capabilities of Shockwave.

For a low-tech alternative to Shockwave and Java, the use of just web pages and perhaps a database is a very good solution. Forms within web pages have become very common and students seem to have no problem using them. As Professor C. Ammon of St Louis University recently mentioned to the author, "no matter what the student's background – from liberal arts to engineering – they know how to shop online. So they can handle a browser and the online forms with no problem!" Using such tools allows more of a cookie cutter format to be adopted with an environment that is less time consuming to construct, yet feedback specific to the student's response can still be given.

During this research, experience was gained with such a tool when developing a fully online class for Introductory Structures for the Boston Architecture Center. The course was hosted by eCollege.com, which provides the capability to build online quizzes with a variety of problem types, including fill in the blank, multiple choice, multiple answer, true/false and matching terms. Although the quiz is a static environment, its power lies in the ability to provide the students with the solution as well as comments directed towards either their specific answer or the problem as a whole. Access to this feedback is provided as soon as the quiz is complete. This means that although guidance is not available immediately to help the students with the next problem during the quiz, they will receive it while they are still mentally involved with the problems and concepts. The students in the class this last Fall semester found the online quizzes to be one of the most powerful assessment and learning tools in the course.

4.1.11 Propose an interactive exercise for each concept

Next, creative ideas for engaging the student with each key concept (i.e. those in the first and second levels of figure 4.1) of the knowledge map need to be developed. The developer probably already has some ideas for simulations and interactive exercises that were actually the inspiration for creating the module. For instance, the exercise in the prototype module on stabilizing the beam, as will be described shortly, was one.

Regardless, when proposing the interactive elements it is important to decide on which method of learning and using a concept, the module should draw on. Which one best encourages internalization of the conceptual behavior for future intuitive understanding? For instance, when asking experts how they check the stability of a body, there is a variety of responses. Some may apply the equation of equilibrium for each direction and check that sufficient reactions are present and that the equations are solvable. Others may determine the rank of the stiffness matrix, which is a mathematical extension of the former approach. Yet, another approach is to visually examine the body and its supports for adequate restraint against any load type. The last technique quickly reveals itself as the most intuitive. To successfully apply it, the experts must have already internalized the rules of the first two techniques to develop the correct pattern recognition and visual skills inherent for behavioral understanding.

The module, therefore, works to provide engagement methods that instill these desired skills, i.e. extending the rule-based skills of, say, the first technique, which the students are more likely to be learning in the classroom. Table 4.2 lists the preliminary interactive exercises drafted for the prototype module.

4.1.12 Decide upon control path through module and between exercises

Although a means for connecting each of these interactive components must soon be worked out, at this point a control path between them need only be established. Two levels to this control path exist; at one level the path just steps from one concept to the next, yet at a more specific level the individual's exact movements are considered

Table 4.2   **The interactive exercises proposed for each concept in the module**

key concept:	proposed interactive exercise:
rigid body motion	display animated examples of rigid body motion and then ask student to identify more examples from a list of different forms of deformation and motion.
prevent rigid body motion	simulation problem of a beam – ask student to stabilize with horizontal and vertical restraints. Potential support locations are at each corner of the beam. Ask to repeat numerous times, learning that there's never just one answer and gradually working towards solution of minimum number of supports (i.e. a determinate structure). Urge towards desired outcomes through accompanying conversation "Is there another way to make the beam stable?", "Is there a better arrangement?"
requirements of stability	multiple choice problems querying the observations and conclusions made from the beam problem.
determinate vs. indeterminate	already inadvertently worked towards with the beam problem. This is observed through more multiple choice problems on the student's conclusions from the beam problem.
how to provide restraint/ support types	use examples and multiple choice problems to test on various support types.
review combining restraint types and rules of determinacy and stability.	second simulation problem with various differently shaped, oriented and supported single elements. Objective is to reduce the arrangement to a determinate structure. Uses typical support symbols (roller, pin, fixed) instead of restraint arrows. Reflects development and summary of all prior material.
assemblies	simulation problem that brings together previous concepts. Consider various assemblies; asking the student to first break assembly down into components of single elements with the correct restraint types provided by each connection; then check each element is independently stable using adjacent elements for necessary support. Ask to conclude if stable or not and if so, how many levels of redundancy.

through each interactive component. This second level is deeply involved with when and how feedback is provided to create a sense of conversation. An estimate of both of these levels of the control path, particularly the general one, is necessary at this stage before the module's interface can be designed.

As already touched on in Chapter 3, the control method adopted for the module is a single path through the module. Specialized feedback is provided at each point, but the next problem presented would always be the same. There is no adaptation to the environment for differences in skill. See figure 4.2. Additionally, (i) all the open-ended simulation problems are repeatable, encouraging play and experimentation, and (ii) the student must attempt all problems at least twice before the solution is available and she can proceed onwards. The choice to reveal the answer is up to the student. Optional hints are also available to steer towards a correct answer. All these design choices have been made to encourage engagement, yet limit frustration and leave control in the student's hands.

An additional reason for choosing a linear control path with all content available to all users was the acknowledgment that the struggling students are not the only ones who want the extra explanatory information. Often the brighter students also appreciate these extra tidbits, expressing their curiosity in the subject by exploring every avenue available.

Very simple adaptability was provided in an earlier module from this research. Simply called "Load Paths", it was a more advanced version of the "Seeing Load Paths" slideshow from the Master's thesis. For a problem with two correct answers, two series of response pages and relevant interactive questions were developed. Each path would gradually come back to re-asking the question, however, in order to get the second correct response and its corresponding set of responses and questions. For a sketch of this control path, see figure 4.3. The prototype module did not explore this idea further, due to the reasons already given. Additionally, the extra level of complexity and
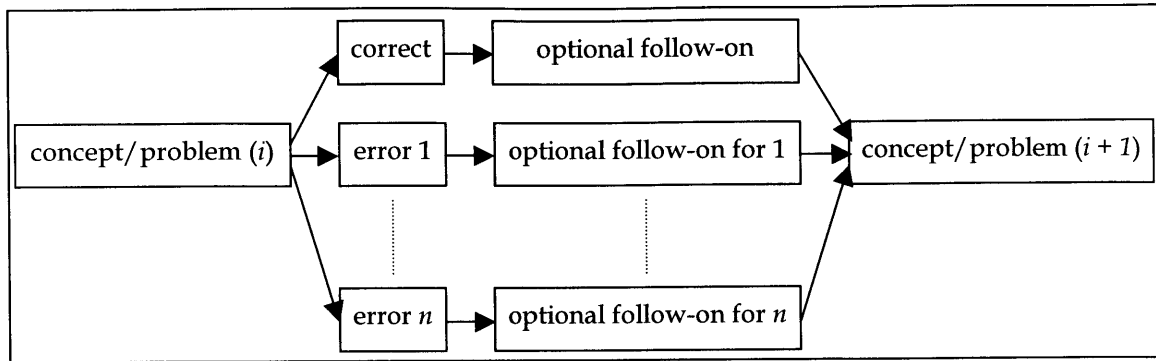
Figure 4.2   Basic control path used in module
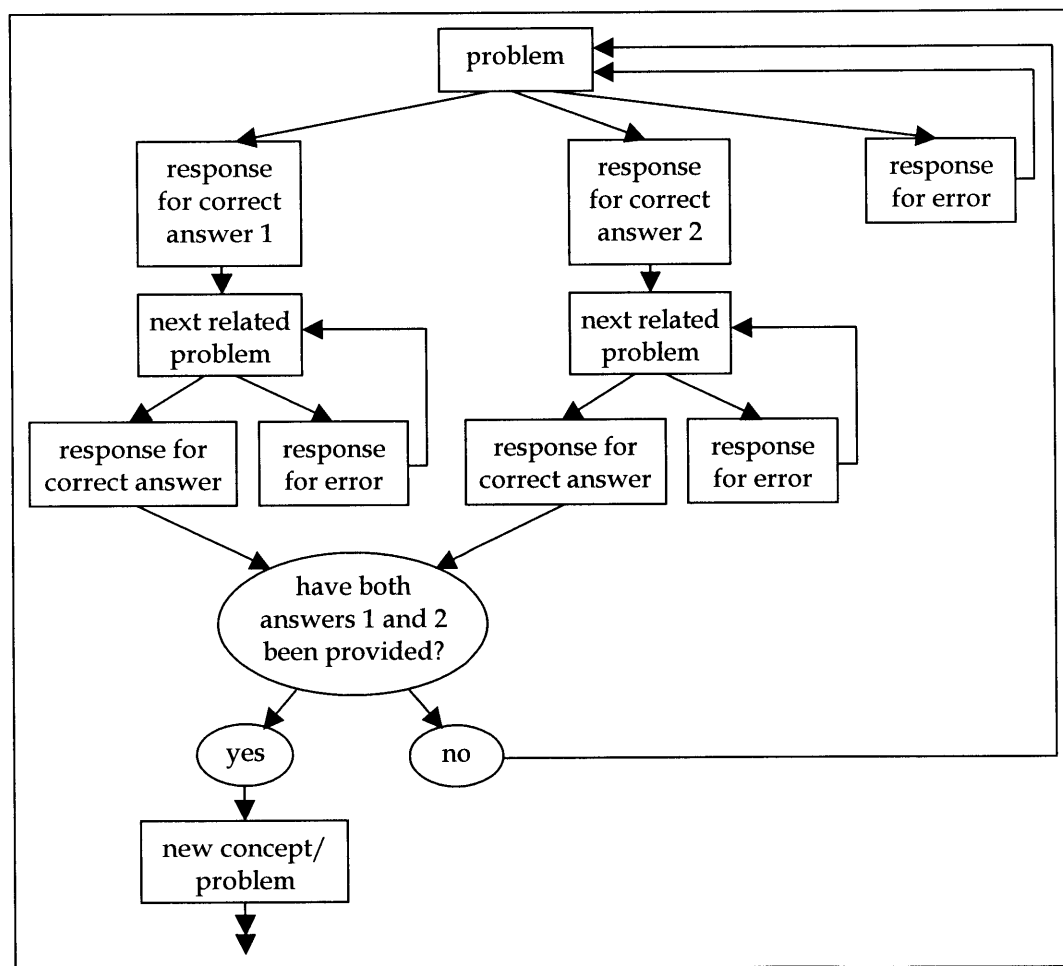
Figure 4.3   An attempt at an adaptive control path as used in "Load Paths" module

challenge appeared unnecessary. A somewhat personalized conversational environment still seemed achievable with a solely linear path.

A possible adaptive control path based on a network of error scenarios is shown in figure 4.4. Adopting such advanced control paths in future modules and learning tools with the help of Artificial Intelligence offers exciting avenues for further research.

4.1.13 Design the graphical user interface and navigation controls

Finally, the actual construction of the module environment can begin. All the previous design steps and decisions were required to know what is required of the computer-aided environment and its navigation methods. At this point, the developer may
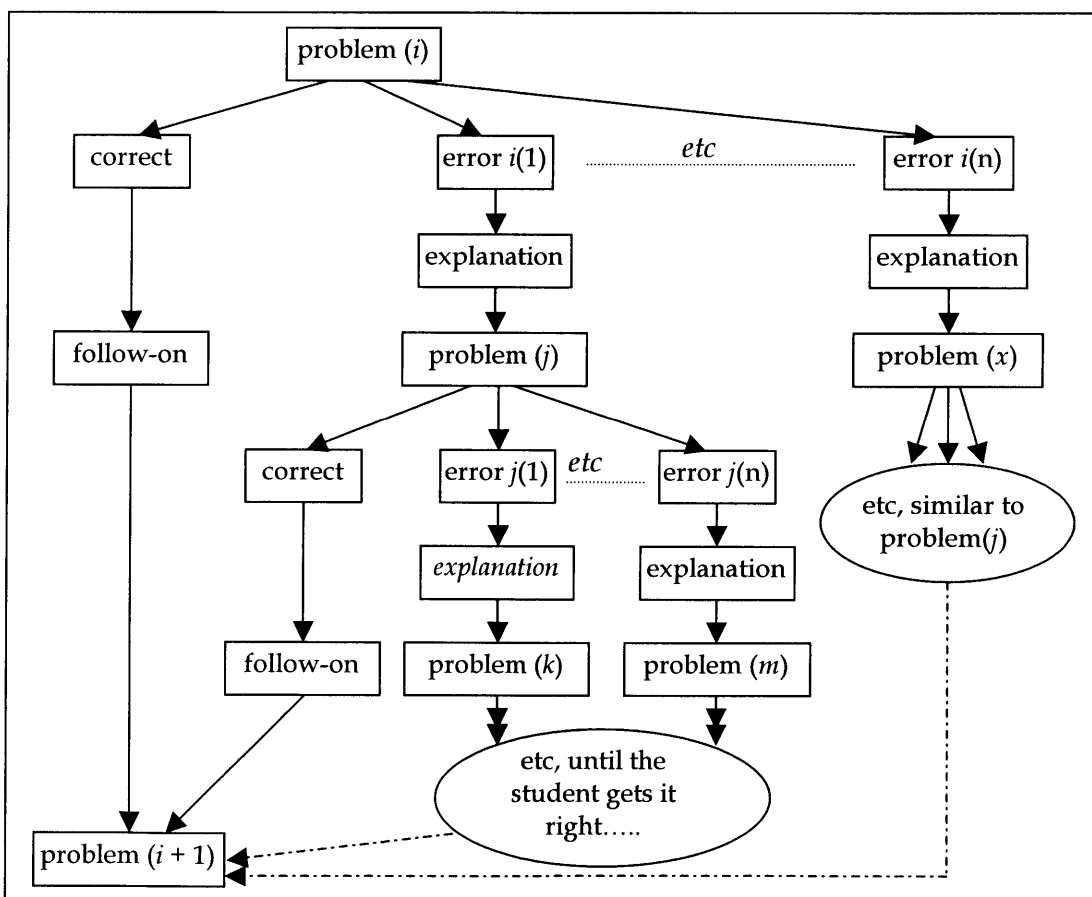
Figure 4.4   A possible adaptive control path

actually review these decisions, particularly the chosen technology, to see how well the computing demands are met.

Typical screenshots of the module's interface can be seen in figures B.1 and B.2. The design decision was made to compartmentalize the information layout, so a region was set to the left for the text and another larger region to right for the simulation and graphics. Text is used in the second region sparely and typically only for annotations, when they are unavoidable. A third hidden region was occasionally used in the form of a popup window to provide the "aside" information when necessary. This is only visible when a hyperlink is clicked and may contain text and/or graphics. It can be re-hidden by clicking on the hyperlink again or within its popup window.

One of the most important components of the interface design is the navigation methods. For the module, the four main navigation controls are:

show me ▶ tell me more **hyperlink**

move on ▽ forward/backward buttons ⬤

These were chosen to capitalize on previously established web symbology as much as possible. They can be seen in action in figures B.1 and B.2. Note how they are used within the "text" region only. As already mentioned, the hyperlink, familiar from web browsers, causes a hidden "tell me more" window to become visible. This typically contains additional background information and is optional for the student to view. It reflects the third layer of the knowledge hierarchy that is further explained in the next subsection.

The play or "show me" button is used to demonstrate a concept or term by either animation or images. Clicking on it causes something to happen in the "graphical" region of the screen. The third control was introduced to represent "move on", i.e. let's continue on to the next piece of information. This control is particularly important for enabling a stepwise presentation of the material and ensuring the student is focused on the appropriate aspect of the screen at any one point. To see this in action, see figures B.2 to B.4. For the new "page" or screen in figure B.2 only an initial section of text is

given. The student must then read it and click the play button or other interaction mechanism. The animation runs and the "move on" symbol is then visible (figure B.3). The student now clicks this button and the next piece of information is displayed, as in figure B.4. Each section of text is typically punctuated by a hyperlink, play button or interaction exercise. The idea is that each of these sections is like a contribution in the conversation that then requires some response or reflection by the student.

The process of revealing text and graphical demonstrations continues until the text region is full and it is time for a new page. Then the fourth navigation control type is used – the forward or back buttons in the bottom right-hand corner. They are located in the same place throughout the module and obviously allow the student to move forward and backward through it. You will note from figure B.2 and B.3, however, that the forward button is not active on the screen until all of its sections of text are revealed.

These navigation controls ensure the desired linear path, with really only one option available to the student at any point if she wishes to progress onwards through the module. All of which satisfies the principle of user-centeredness. The standard controls through the module have now been described; however, each interactive exercise has its own set of controls and buttons. The variety of these is limited as much as possible to satisfy the principle of least astonishment. Typically, the module uses buttons with text labels, i.e. "check answer", "hints" and "tell me". Switches are used also, but again with text labels, i.e. "general load". The location of these controls is preferably at the bottom of the "text" region or if necessary the lower right corner of the "graphical" region. Examples of these controls and their placement within the interface will be seen in the following subsections on the development of the interactive exercises.

In designing the look and feel of the interface, the graphical design principles of section 3.2.3.1 were followed extensively. Kristof's et al "Interactivity by Design" [16] was also an extremely useful resource for the navigation and interaction design. It is felt that the result is professional and pleasing to the eye. A few examples of how the principles were applied include the use of contrasting colors, fonts and framing of regions.

Using italicized, bold text of contrasting color strategically identifies new important terms. A "show me" or hyperlink control is usually associated with the term, figure B.1. Equally, the text associated with a "show me" is always in bold or italics. Different colored backgrounds frame the graphical and text regions of the screen. Additionally, whenever text is used in the graphical region, as either annotation or the layover of the popup hyperlink windows, a "shadow" border to provide contrast and highlight the change in format frames it, figure B.5.

4.1.14 Develop storyboard

Now, we can combine the work on the interactive exercises and control path from sections 4.1.12 and 4.1.13, respectively, to develop an outline for the module, deciding how to present the material within the format of the interface just designed. What will happen on every screen? Having adopted a linear control path, the development of this storyboard is relatively straightforward.

Beginning with the topic's knowledge map of figure 4.1, each sub-topic or key concept is embellished to include the interactive exercises. An outline of the script also begins to experiment with ways in emulating a tutorial conversation. This was achieved by imagining a tutor or expert sitting down with a student and considered how she would break down the concepts for the student, to draw it out and step him/her through it. Additionally, to encourage discovery learning the concepts are presented with as little initial supporting material as possible. After all of these considerations, the result for the prototype was a storyboard. Figure 4.5 presents a portion of this storyboard. In particular, the bold text represents the interactive exercises and the italic represents the "asides". From this figure, the expansion of the knowledge hierarchy can be observed, showing it better developed with each of the knowledge levels being more detailed.

Lastly, as the storyboard and initial attempts of the script develop, the necessary images and animations will also begin to become clear. Begin collecting and creating them early. For the prototype module, producing effective and worthwhile images and animations took a great deal of time and effort.

- explain navigation
- introduce topic

explain topic:
- what is stability?
- what do we mean?
- why interested in topic?
  ...examples

discovery path
- divide and conquer, with animation

if correct

what is rigid body motion?
- give two examples then multiple choice problem to pick more examples from list.
definition of rigid body

explain why examples were and weren't

if correct

- advise how many were correct
- ask to try again, make hint available
- if after two attempts can view answer

if wrong

if view answer after 2 attempts

explain why student's incorrect choices were wrong by considering likely misconceptions

if wrong

give definition of rigid body motion

how do we stop rigid body motion? multiple choice problem

if correct

feedback answer: need more support

if wrong

if correct

if wrong

feedback on choice and ask to try again

but what sort of support? what are issues?
- types of loads
- types of supports (will get to later)

follow up questions introducing/testing:
- lines of action
- unusual stable and unstable arrangements
- coupled end restraint (leads onto for later fixed end support)
lines of action, couple

beam interactive exercise testing:
- how to stabilize?
- what's minimum support req'd?
explain why no *deflection/rigid body*

use beam to explain load types and set up beam interactive exercise.
aside of types of horizontal loads

what are the minimum number of supports req'd? *aside with eqns of equilibrium*

3 – connect with eqns of equilib.

can they be just any restraints?

etc...

if correct

if wrong

feedback on choice and ask to try again

if wrong

Figure 4.5   Sketch of part of the storyboard for the module

4.1.15 Design interactive elements

At this point, the module is beginning to come together, and it is ready for the substance to go within the newly established environment. Thus, the six steps for presenting the interactive elements set out in Section 3.2.3.3 may now be applied. This stage, building the interactive elements, and the next one, providing the framework to connect and support them, cover these steps and are very much intertwined. Typically, steps 2 to 4 are considered by this stage, and steps 1, 5 and 6 by the next stage. The designer will usually consider the stages iteratively, just as was done with the prototype. The best approach is to build each exercise and then the framework around it one at a time, gradually building the module sequentially from the beginning to the end. Crafting these components well is essential to achieve the sense that the student is having a conversation with an expert.

Furthermore, the designer may even find during this development phase that she wishes to review the previous design stages of the module, i.e. the interaction ideas, knowledge map and storyboard, embellishing certain points and adding extra concepts. This need simply reflects the iterative nature of the methodology that may not be apparent by the linear presentation of its implementation here. Please note all of the previously presented design components, such as the knowledge map and storyboard, are the final versions that resulted from multiple iterations.

To examine the design of the interactive elements, some examples from the module are presented. There are two types, the simulation tasks and the multiple-choice problems; the following subsections describe each.

For both of these interactive elements, there were two essential design issues – setting the question or task and providing effect informative feedback to the student's responses to them. With Macromedia's Director tackling these issues for both types of interaction elements is quite straightforward. It has its own programming language, Lingo, which as previously mentioned cannot handle complex analysis, i.e. matrix multiplication and manipulation, but it is capable of the usual forms of control loops

and statements (i.e. if-then-else, and repeat while) as well as storing information in arrays.

These capabilities are used to the fullest to make the interactions as engaging as possible for the student. The module's computer code checks the student's choices when requested by a button click. Through case-based reasoning, using if-then-else and/or case statements, the appropriate feedback response is then provided. Prewritten text responses are stored in hidden text fields and called upon as needed through the scripting.

4.1.15.1 Simulation task design

The module uses three interactive simulations, as indicated in table 4.2 – (i) stabilizing the beam, (ii) checking stability of varying single elements and support arrangements, and (iii) checking the stability of an assembly. Other physical and behavioral simulations are given but these are just animations used as demonstrations or feedback responses to a student's answer in a multiple-choice question. Therefore, the use of these animations will be discussed under the multiple-choice problem design section.

Although, seemingly elementary, the beam exercise shown in figure B.6, is a favorite for its simplicity and the variety of learning experiences it provides. The task for the student is to make the beam stable by dragging up the available supports from the menu in the bottom right of the graphical region of the screen. Force vectors represent the supports, with the arrows indicating the direction of restraint. The beam has four restraint locations, one in each corner, to which a support can be "attached" or dragged. Once an arrangement is made, the student can check if it will work by applying a "general load". Clicking the switch triggers the module to analyze the beam and apply a "random" load via an animation. If stable, the result is no change to the beam and a text response notes that it is correct and asks the student to repeat the problem by finding a different arrangement. If unstable, the beam collapses with an animation indicating its real mode of failure, i.e. rotation as in figure B.7. The accompanying text does not advise the student how the arrangement was wrong, instead the visual

feedback should be sufficient and it asks the student to try again by returning to the task screen. At this point, an optional hint is available if the student would like a little extra guidance.

Once this task has been correctly completed twice, the student is asked to try yet again but this time with the goal of finding the minimum number of supports necessary. If she has already happened to find this then the module would point this out and ask her to find another "minimum" arrangement. Once the student has found at least three different arrangements (including one "minimum") she can then proceed onwards if she wishes. The "minimum support" task in the simulation problem is particularly good as the student is forced to stumble upon the idea of a determinate arrangement and what it means without even realized it or having it specifically asked of her.

Using accurate animated responses to the student's errors as the main feedback encourages visual observation and makes the necessary textual feedback easier to create. The challenge was considering every type of error that the student may make. The beauty of this simulation, however, is for its seeming open-endedness and qualitative nature, it is a rule-based problem where every potential error scenario or support arrangement is catered for by a series of if-then-else and case statements and corresponding specific responses.

For the textual feedback, if incorrect there is only one response type – "try again" and if correct there are two – the case for a determinate arrangement and the case for an indeterminate one. Variety, however, is provided by slight changes in the response for each attempt, so they do not seem too preprogrammed and rote, even though they are!

The main engineering skill of the three to be targeted in the module (c.f. Section 4.1.6) is a conceptual knowledge of geometric compatibility. The student, however, begins to see the impact of her "design" choices, as well as becoming more familiar with such things as a free body diagram (the representation of the beam).

From this description of the simulation task, its ability to force the student to engage with the phenomena and provide feedback responses specific to the student's interactions, should be apparent. The student was also queried on her observations, though only passively. Therefore, as will be described in the next subsection, a more explicit and better attempt was made to test her observations and encourage reflection through a series of multiple-choice problems following the task.

4.1.15.2 Multiple-choice problem design

The multiple-choice problems can be surprisingly creative and effective. They are far more than just a simple question and response, especially with the world of graphics and animations available for demonstrating concepts. The challenge, however, is to provide problems that are stimulating with answer choices that cover most of the students potential misconceptions. Here are three examples on how this was attempted in the module.

The first example is the follow-up exercises on the beam simulation task previously introduced. Their use was briefly mentioned at the end of the last subsection. The main goal of these exercises was to query the student further on her observations and present her with arrangements she may or may not have come up with herself during the simulation task. For each example arrangement, the student is simply asked if it is stable or not, see figure B.8. Then if it is unstable, she's asked to predict how the beam will fail by indicating which point it will rotate about, figure B.9. Once answered, for both the stable and unstable arrangements, comments can follow indicating certain interesting aspects (i.e. lines of action, couples), as in figure B.10.

These follow-up problems are very powerful, as they ensure the student has seen certain arrangements that are enlightening with a particular learning experience. Furthermore, these follow-up problems allow the opportunity for a detailed and specific discussion that was not easily achievable during the simulation. This approach can also allow the opportunity to feed into concepts found further ahead in the module. For instance, the last beam arrangement with a coupled force end arrangement was chosen as it perfectly

sets up the discussion and exercise on fixed connections that follow further on in the module.

The second example is the rigid body motion exercise that was near the beginning of the module. This one uses the multiple-choice concept a little more interestingly. First two examples demonstrating rigid body motion through an animation are provided – books falling on a shelf, figure B.11, and a simply supported beam with a removed support, figure B.12. Then without providing any further explanation beyond these examples of what rigid body motion is, the module asks the student to select from a list other examples of the behavior, also seen in figure B.12. The student is challenged to observe and compare the given examples and then make her own judgment on what might be in common between these examples and the potential ones in the list. One small optional hint is provided with the hyperlink on rigid body that provides a definition of a rigid body as well as clarifying some related aspects, such as they do not actually exist in real life, etc; see figure B.13.

Upon checking her answer, if incorrect, the module tells the student how many are correct and asks her to try again. As usual, an optional hint is available. After two attempts if she still does not have it right, the student has the option to continue on and be shown the answer, or try again. If shown the answer, an explanation is then provided that is specific to the choices she made, explaining why the ones she got wrong were wrong and recognizing the probable misconceptions. This demonstration of deep, informative feedback is seen in figure B.14. If the student had made the correct selection, the module congratulates her on her good work and reiterates the correct answers for reinforcement.

Not until this exercise has been completed and the feedback given is the full definition of rigid body motion actually presented, purely for the purpose of providing clarity and summarizing the conclusions on the concept that the student should have made on her own. By this point, the student is ready to move onto the next concept.

The last example is one of the connection problems – the roller in figure B.15. This time the module presents an image of a support and asks the student to decide what form of restraint it provides by selecting from the set of restraints at the bottom of the screen. Again, two attempts are required before the option is available to view the answer. With the responses, the feedback is specific to her choice, whether right or wrong. The follow-up explanation and summary then provides reinforcement and not until this point is the student actually told the support is a roller, figures B.16 and B.17.

The key to this problem's effectiveness is that no supporting material is given. Instead, the module challenges the student to call on her intuition and give an opinion. The environment is designed to make the student feel as safe and confident in making such choices as possible. One important design choice that assists with this and was used with all the exercises is the "check answer" button. Only once the student has made a choice from the list (or similar) and then confirmed this choice by clicking the "check answer" button, is a response given. This limits any surprise or accidental actions by either the module or the student. In turn, this allows reflection on the problem by the student before she commits, encouraging less hesitancy and more confidence in her actions. Both the principles of least astonishment and user-centeredness are satisfied.

From all these examples, the key challenge is seen to be considering the choices for the problems so as to reflect qualitatively the likely misconceptions of the students and then to provide responses that recognizes these. The rigid body motion exercise attempted to deal with these issues particularly well. Another good approach is to ask the student to predict the consequences of an experiment, based on her observations of a simulation, or similar. This idea was brought out somewhat in the beam follow-up questions, when the student was asked to predict how an unstable beam would rotate.

4.1.16 Build framework to connect exercises

With the exercises built, they must now be embedding into an explanatory framework that strings each one together. Providing this last aspect of the module is an essential step for creating a sense of tutorial conversation and encouraging qualitative reasoning.

The framework for each exercise tends to take the format of:

introduction ➔ task/problem ➔ conclusion ➔ segue into intro for next exercise, etc. The amount of introduction, conclusion and segue varies depending on the exercise and concept, but ideally the more each concept builds on the next, the less "padding" is needed.

How the conclusions (summaries) and segues are provided has already been covered implicitly by the previous interactive examples. They are not difficult to develop if the storyboard is well designed. As already noted, when presenting the interactive examples, the module forces the student to make her own observations and conclusions on each key concept before it will present its own summary. In doing this is important, however, that the student is guided to make the *right* conclusions. Therefore, the problem usually needs to be "setup" or introduced, particularly the simulation tasks, to remove any ambiguity.

The beam simulation example, figures B.18 to B.22, again provides a good example of this necessary setup. During the preliminary evaluations of this task, it was quickly recognized that the student's couldn't just be shown a rectangle and told it's a beam that she must stabilize by putting supports on to it. After all, the first time the beam is displayed, which is without any supports, it will look like its holding itself up just fine; why does it need any help? Therefore, the context and environment of the beam must be explained from the beginning.

Therefore, as seen in figure B.18, the beam is initially presented in a gravity free world where it could safely float. Then the student can see what happens when gravity is turned on, figure B.19. The setup continues demonstrating how restraint is needed and can be provided for gravity as well as a "sideways nudge", figure B.20. Thus, both the vertical and horizontal load types are considered. Furthermore, this is the prefect opportunity to remind the students of the oft-forgotten horizontal forces and how they always need to be catered for. An aside is provided on common types of horizontal loads, figure B.21. Next, the module actually presents a solution for stabilizing the beam

for all the forces, figure B.22, where all of the available restraints are used. This serves the purpose of showing what is required of the student but also eliminates one to the "obvious" answers – using all the supports, which is a little extreme! The other "obvious" answer – no restraints at all – has also been eliminated. By now the student has seen the two extremes and is asked to find better solutions that lie somewhere between them. Furthermore, the horizontal nudge and gravity loads are combined into a random "general" load that could act in any direction, figure B.6.

Going through this slightly laborious process removes any ambiguity by anticipating students' confusions as well as setting the student up to work with the simulation task more efficiently. Furthermore, the resulting interactive exercises and supporting framework work well to satisfy the learning goals of Section 4.1.7. This is demonstrated by the examples given. They encourage students to perform reflective, critical thought and consider the consequences of their actions. Both are very good skills, for the student to return to her analysis techniques from class and better understand what is meant by them.

When considering the module as a whole, it too has its own introduction and conclusion, which bookend the string of key concepts and their exercises just described. The introduction of the module explains how to navigate through it, introduces the topic and its scope and then presents the learning goals. Through this supporting information, it is important both to provide relevancy (why would the student be interested in stability and the module?) and to sketch out the discovery path that the student will be going through. The module's expectations must also be made clear. Some of these early screens of the prototype module are shown in order in figures B.23, B1, B24, B4 and B25.

The significance of stability is explained through its effect on everything from simple elements (i.e. beams) to assemblies, figure B.24. This leads well into presenting the discovery path, using just a simple animation of "divide and conquer" and explaining that the module will take the student from one end of this process to the other, figure

B.25. This all prepares the student for her path ahead and allows a moment to adapt to the learning environment.

The modules' conclusion is quick and easy to prepare as the process should have been one of incremental knowledge building. Its purpose is to close the loop of the student's learning experience with a reflective moment. Therefore, it is simply a recap of the steps covered, demonstrating to the student how she did actually proceed along the discovery path and achieved the required goals. The concluding screens are shown in figures B.26 and B.27.

4.1.17 Review and testing

Although the module may now seem like its finished by the discussion provided so far, there is still one essential step to be done. As already alluded to in the earlier subsections, the module must be reviewed and tested. Reviewing is necessary to ensure the fluidity of the module's conversation, check for consistency in the terminology, and finalize the knowledge hierarchy. The testing discovers any potential ambiguities and trials the interaction and navigation methods. For instance, such testing discovered the need for the detailed setup of the beam simulation task.

To evaluate the module, there should be periodic small tests throughout the module's development for fine-tuning as well as a final testing stage. Potential users and colleagues should be used as targets for both of these forms of testing. Already throughout the presentation of this implementation, many of the fine-tuning aspects were covered. For the final testing of the prototype module, a detailed evaluation was carried out, but its goal was also to evaluate the methodology and its effectiveness. Therefore, this step was an important aspect of the research and the full details of both the process and the results are provided in their own chapter, Chapter 5.

4.2 A library of modules

The idea of a library of modules was developed during the author's work on her Master's thesis. After the amount of effort focusing on completing one module well, however, this seems very ambitious. The idea is excellent, though, and definitely, the best means for the learning approach and methodology to cover a full spectrum of knowledge. Regular use of the modules and the environment by the student will also better ensure the modules become an effective and accepted aspect of her learning experience.

Therefore, this module should be seen as one of a series, and as a whole, the library would cover the full knowledge map of Appendix A. Recall from the teaching context set out in Section 4.1.5, that each module would be available as a weekly homework assignment. At an earlier stage of this research, a possible integrated environment that these modules may sit in as a part of a class project was developed with Abel Sanchez, for Brackett's "T522: Education Software Design" class at the Harvard Graduate School of Education [2]. The interface for the contents page is shown in figure 4.6.

The module on "Seeing Load Paths" mentioned earlier (c.f. Section 4.1.12), as it explored adaptive control paths, was developed as a module to fit into this environment. Figure 4.7 shows a screenshot of one of its pages. An exciting aspect of this design exercise was considering the extra capabilities and tools to integrate and enrich the environment. The menu column on the right of the page displays some of these features: email, a chat facility and access to the student's own progress report. When designing this environment, it was envisaged that the student would log in, and therefore identify her work. A database would then collect and monitor their results via the web. The summary of these results would then be available to both the student and the instructor as the progress reports. This capability could be very powerful as it not only personalizes the experience for the student, but it also allows the instructor to monitor class trends, weaknesses in the learning process and an individual student's progress. Other tools for the environment could include a glossary and search capabilities.
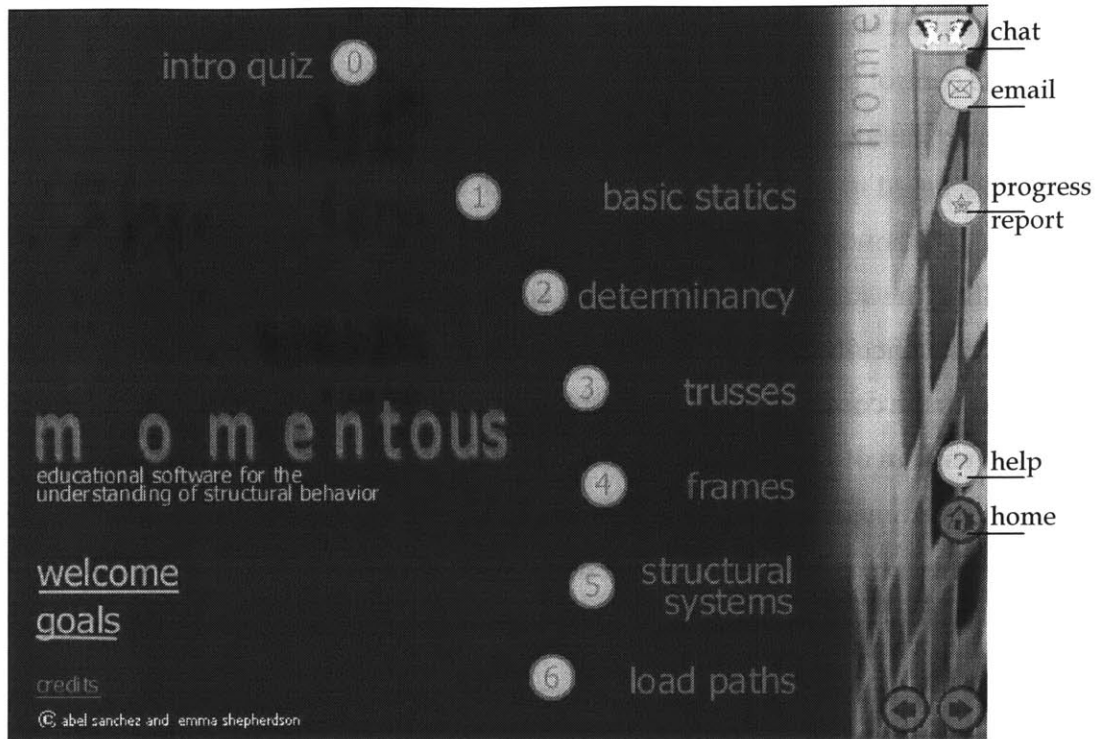
Figure 4.6   **An example of a possible contents page for a library of modules and their environment**
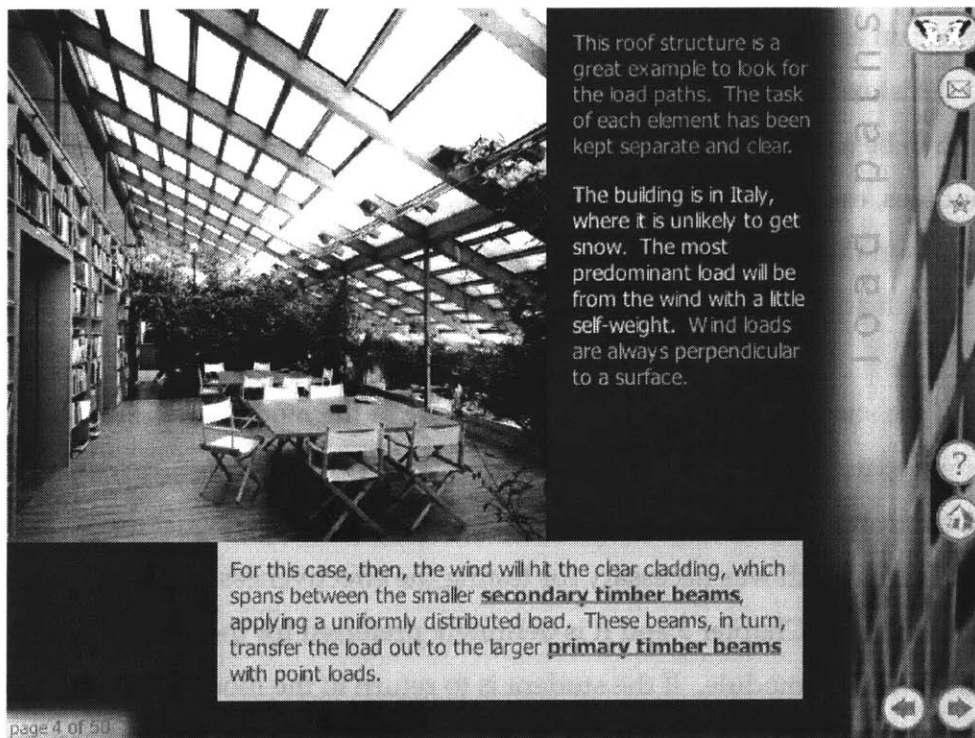
Figure 4.7   **A page from an earlier module design, displaying the enhanced features of an integrated environment**

The important issue, however, when designing such an environment and its modules is how the control path of each individual module will interact with the others. How much interlinking between them is desired? Some of the concerns involved with this were discussed in section 4.1.5. On one hand, the library can enable a wonderful network of knowledge for the student to wander through; yet, on the other hand, controlling the student's movements to ensure focus on the specific topic is a key design goal. It is difficult design task, therefore, to search for the right balance. A possible solution is the compartmentalizing of the module into smaller components that can then (i) be reused in other modules (creating overlap) or (ii) provide opportunities at the end of each component for branching off to other related topics in other modules. It is an interesting dilemma that really depends on the decided teaching context and what would allow the most flexibility and potential future use of the modules by students all over.

For instance, the prototype module presented here could be broken into at least three sections or components – one on stabilizing single elements, one on connection types and another on assemblies. As the prototype was longer than ideal, due to various research decisions and testing purposes, each of these components could possibly even be enough to be a module of its own. Alternatively, the sections could be reused for other modules, especially say the one on connection types. It is felt, however, that breaking down the module any further than these three sections would disrupt the discovery path and cloud the learning goals too much.

Recall that the student must go from the beginning of the module to the end with no opportunity to jump ahead. This is not an ideal arrangement for future inclusion into a learning environment and library with such enhanced facilities as just discussed. This restricted control path was necessary for testing the effectiveness of the methodology as will be described in Chapter 5 and it is definitely preferred for the student's first experience with the module. If the student is to return to the module, however, for review or reference she will very likely wish to move around and jump ahead to specific areas of interest. Using the capabilities of the aforementioned environment both of

these preferences can easily be achieved. The student could log in and experience the module for the first time from the beginning to the end, as presented in this chapter. Then when she returns for another viewing, her previous efforts would be remembered and a different front page could be presented. This page could display a contents menu, that allows her to jump forward and backwards through the module, as she desires.

4.3 Conclusion

This chapter presents a prototype tutorial module on *"rigid body stability"* that implements the design methodology described in Chapter 3. The module can be seen on the enclosed CDrom. Although presented as an implementation, the research efforts actually used the building of this prototype as an opportunity to evolve and clarify the methodology.

In developing the prototype, every effort was made to meet its specific learning goals that were set out in Section 4.1.7. It is felt that these goals were achieved well, but just how well is to be decided by students from the target audience evaluating the module. Chapter 5 attempts this evaluation, using the module as the probe to exam the effectiveness of the design methodology, which it employs.

Chapter 5

Evaluation of the methodology

Ensuring the effectiveness of the developed methodology is an essential aspect of the research. Students from a range of schools, both Civil Engineering and Architecture, used the prototype module for the evaluation. The process and results are described in this chapter. Section 5.1 outlines the purpose, Section 5.2, the procedure and Section 5.3, the results and initial observations. A variety of issues with the methodology and the evaluation process were raised because of this work. Disappointingly, not all of these issues were positive and they are discussed in Section 5.4. Section 5.5 concludes the chapter with a summary of the findings and recommendations.

The main guidelines used when carrying out the evaluation were "The User-Friendly Handbook for Project Evaluation" [32], published by the Directorate for Education and Human Resource Development (EHR) of the National Science Foundation (NSF). As stated in this guide, evaluation means different things to different people; however, a single general definition is also presented:

"Systematic investigation of the worth or merit of an object..."

This definition reinforces that the evaluation is done for a purpose, with its outcomes

allowing not just a measurement of the project's success, but also direction for future work. Therefore, the evaluation of the methodology has a clear purpose and procedure, as presented in the following sections.

5.1 Purpose – questions of evaluation study

In order to measure the impact of the methodology, it was important to put it through a process of evaluation. As an important component of this research, the process uses the module as a probe to assess if the extensive efforts to engage the student were effective. The measurement was made by looking at the target audience to see if the module's learning goals, outlined in Section 4.1.7, were satisfied. Was there an improved understanding of the specific topic, rigid body motion, and its subtopics? Even better, did the students gain a better comprehension of the in-class material?

The unavoidable problem with using the module to test the methodology is that the module is also being tested. Therefore, to ensure the best and "truest" evaluation, it is important that the module is satisfying the requirements to the best of its abilities. In an attempt to do this, the module underwent preliminary testing during its development and the majority of it was checked. The last portion (approx. ¼) of the module, which introduced some informative and critical results, was not pre-tested as comprehensively, however. Unfortunately, besides the best of efforts to follow the methodology, this last portion was found to be too complex and slightly deficient at following the requirements. The impact of this will be seen in some of the results.

As mentioned in Chapter 4, the module was stretched beyond the ideal length in order to provide for better evaluation. Evaluation purposes dictated a larger learning experience that leaves an impression on the student by fully engaging them for a worthwhile portion of time. Furthermore, it was felt that covering more content within the topic would also be useful for evaluation. It is important to mention these design decisions and reasoning in the early stages of this chapter, because results and observation showed that the longer format did not always have the desired effect and had an interesting influence of its own.

5.2   Procedure

This section focuses on the full evaluation process for evaluating the methodology. The adopted process was summative, measuring the impact both qualitatively and quantitatively. Members from the target audience, students in their introductory structures class, were asked to participate. To achieve the purpose of evaluating the students' understanding of the topic and other skills related to the learning goals of Section 4.1.7, a pre-test was given. The module followed and then finally a survey and post-test, similar to the pre-test. The results of these were then gathered for analysis. Lastly, additional data was collected from the module itself. Once completed, the student sent her interaction results online to a central database by the click of a button. The full evaluation process was envisaged to take approximately an hour and a half.

Furthermore, to provide the baseline control for comparison of results, half of the audience was given an alternative version of the module that covered the same material yet it had all of the interactive elements removed from it. It shall be referred to as the control.

The following subsections provide further discussion on the design of each of these components of the data collection.

5.2.1   Audience

Getting the students to participate in the evaluation was the greatest challenge and variable in the process. As will be seen in Section 5.3.2, the ability to reach members of the correct target audience had a major effect on the results. Many universities were invited to participate, including the civil engineering schools at University of Illinois, Urbana Champaign (UIUC); Washington University, St Louis; Northeastern University (NEU); Tufts University; Worchester Polytechnic Institute (WPI); University of Massachusetts, Amherst and Lowell; and of course MIT. The first two schools are co-affiliated with MIT through the Mid America Earthquake Center (MAE Center), the sponsors of this research. Local architecture schools were also called on: Harvard

Graduate School of Design (Harvard GSD), the Boston Architecture Center (BAC), Wentworth Institute of Technology (Wentworth or WIT) and again MIT. The professors and instructors for the introductory Structures class at all of these schools were contacted.

5.2.2 Surveys

The survey was designed with two sections, one to obtain a sense of the student's background and the second to collect her personal feedback on using the module. A copy of the complete survey is in Appendix C, Section 2. Section 1 contains the instructions on how to do the evaluation, which were given to the students.

The inquiry into the student's background had a range of objectives. To check that the student was from the target audience, she was asked what her current Structures class was and what past classes she had taken. Requesting her to self-evaluate her grades provided a sense of the student's ability, while inquiring of the student's interest, allowed a measurement of her potential curiosity and receptiveness to the material and approach of the module. Lastly, asking the student if she had a favorite engineer or architect indicated firstly, the student's interest, but more importantly, how much exposure she has had to the history, culture and context of structural engineering.

The second section of the survey used rating scales to request the student's opinions on the module and the methodology. Surveyed categories included those specific to the idea of teaching concepts, such as interest level, relevance and challenge, and those related to the learning environment and approach, such as the length, pace, interface, help, text and animations. Additionally, the student was asked the time it took to complete the module and how she would rate her prior knowledge of the topic. Lastly, the opportunity to provide comments was available for every survey category.

5.2.3 Tests

The pre- and post-tests were the same in format; both tested the material *covered* by the module and the material *beyond* the module. To remove bias, neither was developed specifically to be a pre-test or post-test. Instead, the two created tests, test A and test B, were designed to be swapped around and used in both roles, i.e. for one school, test A was the pre-test and test B was the post-test, while for another school, test B was the pre-test, etc. Appendix C, Section 3 presents the two tests.

Each question evaluated the student's ability with respect to the module's learning goals from Section 4.1.7. In doing so, the subtopics of rigid body motion were also tested. Each question focused on a single goal or set of goals to test. Therefore, the challenge was to ensure that the question was crafted correctly to give the desired measurement of the student's ability with respect to the chosen goals. Table 5.1 demonstrates how this was achieved.

Furthermore, when creating these test questions, the guidance from R. Slavin's "Research Methods in Education, a practical guide" [30] was abided by:

> "The goal of an achievement test item is not to separate 'smart' students from others, but rather to reliably separate students who have learned something from those who have not. Ideally, every item should be passed by some students and failed by others."

The previously mentioned preliminary testing, done by engineering students at MIT and UIUC, was very useful in ensuring this goal by identifying the weaknesses and allowing the necessary adjustments to create the final tests just presented. For instance, an early stability problem similar to question 6, test B, was shown to be far too complicated and confusing. Additionally, too many reaction/free body diagram (FBD) problems could cause the students to get jaded and therefore put in an effort below their abilities. The students were typically being asked to do this evaluation as an extra to their class and, thus, it was a favor. Therefore, only three FBD problems were used on each test.

Table 5.1   The specific goals tested by each question in the pre- and post-tests

question number	problem type	purpose of question / goals tested
1.	equations of equilibrium (2D)	• checks for prior knowledge of one of the few prerequisites for the module.
2. (i)	check if a single body is stable	• understand stability • apply equilibrium and stability requirements • understand the effect of different types of connections
(ii)	if stable, check if determinate or not	• identify determinate and indeterminate structures
	if unstable, add supports to make determinate	• able to make a rigid body stable • identify determinate and indeterminate structures
3. (i)	check if an assembly is stable	• differentiate between a structure and a mechanism • achieve a conceptual knowledge of geometric compatibility • understand stability • apply equilibrium and stability requirements • understand the effect of different types of connections
(ii)	if stable, check if determinate or not	• identify determinate and indeterminate structures • recognize redundancy • understand the effect of different types of connections
	if unstable, fix to make determinate	• able to make a rigid body stable • identify determinate and indeterminate structures • apply equilibrium and stability requirements
4.	calculating the reactions for a determinate structure; requires the ability to draw a correct FBD	*a performance assessment* • apply equilibrium and stability requirements • understand the effect of different types of connections • gain enhancement to classroom knowledge by focusing on behavior
(i)	a cantilever beam	• an easier problem – for comfort and reassurance
test A(ii)/ test B(iii)	a 2D figure/frame	
test A(iii)/ test B(ii)	a structure with an internal hinge	
5.	predict deformation for a structure	*conceptual testing; more advanced problem* • achieve a conceptual knowledge of geometric compatibility • follow and identify load paths • gain a sense of the bigger picture
6. test A	tension/compression structures	• differentiate between a structure and a mechanism • achieve a conceptual knowledge of geometric compatibility • follow and identify load paths
test B	stability of a 3D frame	

5.2.4   Interaction data and modifications to the module

To allow analysis of the students' level of engagement with the module, the interaction data was collected by the module for each student progressing through it. Once the student got to its end, there was then a button that she was asked to click to send the full set of data to a central database. The data was gathered for each interaction exercise, and simply included the number of attempts the student made on each and whether she got it correct or not before continuing. A randomly generated ID number identified each student, i.e. M444 (see figure B.23). This ID number was sent with the interaction data to identify it and link it to the student's test and survey results, on which the student had also been asked to note the number.

The only other modification made to the module in preparation for the evaluation was the inclusion of a modest crash protection mechanism. Six students in the Structures I class at the BAC were the first to assist with the evaluations. They were taking part in an online class taught by the author. These students' efforts were used to test the system under field conditions. The results helped to quickly highlight performance flaws in the module, allowing for some quick patching. This disqualified the six students' results from the final evaluation analysis but improved the overall process for testing in other the schools.

The main issue these students incurred was the effect on the module of a lost internet connection. It typically caused the module to crash and required the student to start over again. Recalling from Chapter 4, a key aspect of the module is that it requires the student to complete it, starting at the beginning to working through to the end with no opportunity available to skip ahead. Therefore, obviously, something that interrupted this experience and required the student to start from the beginning all over again quickly became frustrating. Therefore, the module was designed so that when the student re-launched its web page, the module would start again, where it had left off. This worked only if the student stayed on the same computer. Surprisingly, this problem was not noticed until this early round of testing. The BAC students also identified a few other small bugs with the modules that were quickly fixed.

5.2.5   The control

In order to measure the effectiveness of the module and methodology, it was best to provide a control to compare against. Finding a control in information technology and teaching aids is typically quite a challenge; these technologies and aids are always changing so comparison is difficult. Secondly, one must take into account the "Hawthorne Effect", which posits that a positive educational result may arise merely by the introduction of something new, regardless of the actual technology. The control used for the evaluation was a Shockwave movie with exactly the same content, interface and navigation controls as the module, but with all the interactive elements removed. Instead, the information was merely presented and the result was a multimedia slideshow with interesting graphics and animations.

The evaluation for this control followed exactly the same process as the module. Although anticipating the response data to also be positive due to the "Hawthorne Effect", there was hopefully a difference. Therefore, the control provided a baseline from which to compare the module's results. The ID numbers generated by this baseline control were differentiated from the modules' by using a B, i.e. B222.

5.2.6   Distribution of the Evaluation Package

Designed to be of minimal inconvenience to the instructor, the process was fully available online. The surveys and texts were presented with instructions in a complete package, via a portable document format (PDF) file, that was to be printed, completed and returned to the instructor. This allowed easy distribution of the packages, as the instructors were simply given two web pages to direct their students to – one to evaluate the module and a second to evaluate the control. Figure 5.1 provides an example of the introductory web pages for evaluating the module. The instructor was asked to distribute the "module" page to one randomly created half of the class and the "control" page to the other half. The rest of the work was up to the students. Once the material was completed, it was returned to the instructor who upon collecting all of the results forwarded them on for analysis.
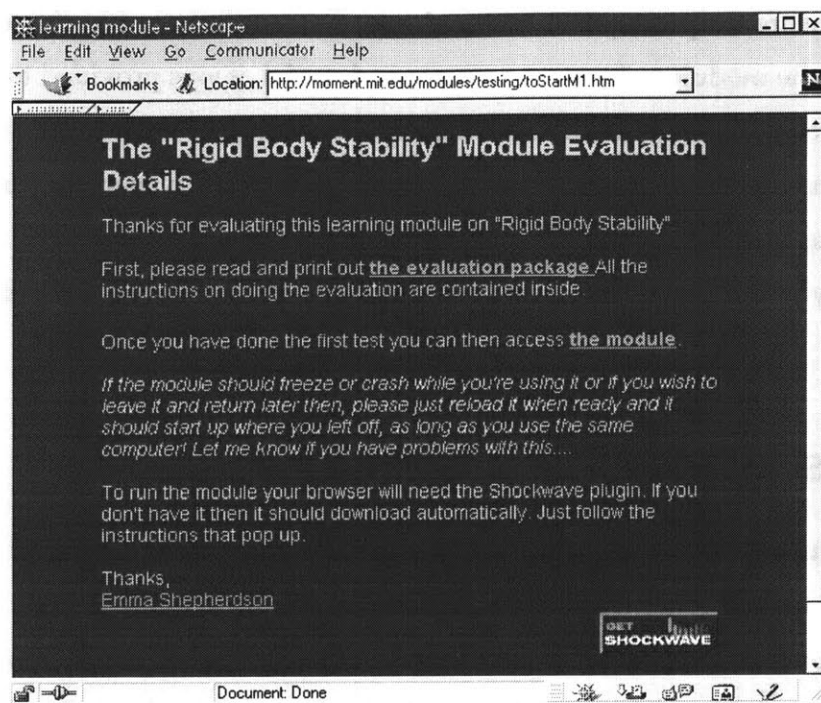
Figure 5.1   **An example of one of the introductory web pages that the student was directed to begin the evaluation and access the module/control**

To allow for the different test order mentioned in Section 5.2.3, there were two versions of the aforementioned web pages, one set for the module and control with a test order of A, pre-test, B, post-test and then a second with B, pre-test, A post-test. Each school was then sent one of these sets, i.e. the architecture students at MIT were given test order A-B, while the MIT engineering students received B-A.

Through the benefit of the web, the evaluation design achieved its goal of causing minimum inconvenience to the instructors. The only potential shortcoming of the process was the browser plugin necessary for running Shockwave. If needed, the plugin was supposed to be relatively easy to install, with the browser providing all the necessary guidance. Unfortunately, computers do not always behave the way they are supposed to, as is well known to anyone with a computer. So, occasional hiccups in execution caused some frustration for the students.

The scheduling of the evaluation was set for October 2000; early enough to avoid the heavy workload demands at the end of the semester, yet just far enough into the

semester to ensure the prerequisite material was covered in class. Ideally, for the evaluation of the module to be most accurate and useful, it was provided to the student as an integrated component of the learning experience for her course. As a rule this was, unfortunately, difficult to achieve due to the need to reach as many students as possible through a range of schools with differing agendas. Consequently, students were typically volunteering and were considering the evaluation as a one off "try out" experience.

5.3 Results and Initial Observations

Carried out during the middle of the fall school semester in 2000, almost 80 students evaluated the control and module; thus, producing a large amount of data. Sections 5.3.3 to 5.3.5 present the results for each aspect of the evaluation: the survey, tests and interaction data. With respect to satisfying the goals set out by the evaluation (c.f. Section 5.1), unfortunately, these results were disappointing. However, there were still some very interesting and informative issues revealed. Section 5.4 discusses these issues and what caused such a disappointing outcome, by summarizing the key observations from the results.

5.3.1 Testing the system by the students from the BAC

As previously mentioned in Section 5.2.4, the six students in the online class for Structures I at the BAC, participated in the preliminary testing. They tested the module under field conditions and recommended many of the last minute modifications to the process and module that allowed everything to run smoothly for the future evaluations. Because this testing focused on the process, etc rather than the module's expression of the methodology, the BAC students' results for the surveys and tests were invalidated for analysis and so are not included here.

5.3.2 Audience

After asking all of the schools mentioned in Section 5.2.1 to participate, the only ones that did were Harvard GSD, Wentworth, NEU, MIT engineering and MIT architecture.

Table 5.2   The number of students and their background used to test the module and the control

school and discipline	module			control			test order	year (typically)	typical number of previous Structures classes
	male	female	total	male	female	total			
civil engineering:									
MIT	1	2	3	1	1	2	B-A	Sophomore	0
NEU	5	0	5	5	2	7	B-A	Junior	2
architecture:									
MIT	3	0	3	2	2	4	A-B	graduate (y2)	1
Harvard GSD	1	1	2	2	1	3	B-A	graduate (y1)	0-1
Wentworth	19	12	31	11	6	17	A-B	Sophomore	0
total	*29*	*15*	*44*	*21*	*12*	*33*			

The author is very grateful to those who assisted. The low response rate and rather diverse background of the participating schools did have quite an effect on the final results, however (see Section 5.4). Table 5.2 summarizes the number and range of students tested.

Although, a reasonable number of students participated with a satisfactorily diverse background, unfortunately they did not all quite fit the requirements of the target audience that the module was designed (c.f. Sections 4.1.3 and 4.1.4). The MIT engineering students were the ones closest to representing the target audience. They were sophomores taking their first structures class, "1.050 Solid Mechanics", in which they were being introduced "*to the fundamental principles and methods of structural mechanics. Static equilibrium, force resultants, support conditions, analysis of determinate planar structures....*" [20]. From this section of their course description, it is clear that gaining their participation was right on target. Prof L. Bucciarelli, referred to in Chapter 2, was the teacher of this course.

The other engineering students, those from NEU, were further advanced, however, as being juniors they were typically taking their third structures class, Structural Analysis I. This class reviewed reactions, shear and bending moment diagrams, forces in a truss and deflections. Therefore, all of these students should have been very familiar with the

principles and concepts covered by the module and the tests, as most of it was taught in their first course, Structural Mechanics I.

The architecture students also represented different course levels. The Wentworth students tested were taking "ARCH240 Design of Steel and Wood Structures", a sophomore class. Wentworth teaches structures slightly differently, by introducing the topic through the various types of construction materials. From the course catalogue [35], the subject is described as "*A study of the selection techniques, analysis, and design of wood and steel statically determinate structural building elements, including beams, columns, rigid frames, arches, and trusses. The concept of indeterminate structures and plastic design are introduced....*". As their first structures class (a small portion of the students (7) were concurrently taking "Heavy Construction", a class that focuses on construction technologies rather than the principles of structural engineering), it would appear to fit the requirements of the target audience. However, after further consideration of the subject description and their poor performance in the tests to be presented shortly, the Wentworth students actually appeared to have been too elementary.

The Harvard and MIT architecture students were part of graduate architecture programs and so were more mature students, adding yet another potential effect The Harvard students, however, were still of the target audience as they were taking "6201 Analysis and Design of Building Structures I", their first class that introduces "*the analysis and design of structural elements.... covers the fundamental principles of statics.... rigid body equilibrium, shear forces and bending moments...*" [15]. The MIT students were in their second class, placing them slightly above the target audience. The class was "4.442 Introduction to Building Structural Systems II" which "*continues the exploration of structural elements and systems; expanding to include more complex determinant, indeterminant, long-span and high-rise systems....*" [20] Therefore, although these students are more advanced they should find the topic relevant to their current class work.

The significant consequences of many of the participating students not fitting the profile of the target audience perfectly are considered in the presentation of the results and observations, that follows.

5.3.3 Survey

5.3.3.1 Student Profiles

Much of the information collected from the first part of the survey (the personal details) is presented in the previous section when the audience was profiled. The only data not yet included are the student responses to the last few questions, which were with respect to their grades, their interest in and desire to be a Structural engineer, and if they had a favorite engineer/architect. These results, therefore for completeness, are summarized in tables D.1.1 to D.1.3 in Appendix D, Section 1.

From this survey information, the students were seen to generally like engineering, regardless of their discipline, though not many of the engineering students wished to work as structural engineers. As no great surprise, the architecture students typically had a favorite architect they could mention. It is a shame though, that the same cannot be said for the engineers having a favorite engineer or architect. This result merely reflects the complaints purported in Chapter 2 with respect to the poor roundedness of the education of engineers. The final interesting observation to be made on these results is that the more mature architecture students at MIT and Harvard also often had a favorite engineer, while the undergraduate level architects at Wentworth did not. Perhaps this is a comment on the strong structural focus that MIT and Harvard encourage in their students, more than anything else.

5.3.3.2 Students' feedback on the module/control

The results of the second part of the survey, opinions on the module/control, are given in full in Appendix D, Section 1. Each category has a pair of histograms presenting the number of people who selected each available option; one is for the module and the other is for the control. Within each graph, the results are broken down into the schools and the same legend is used throughout.
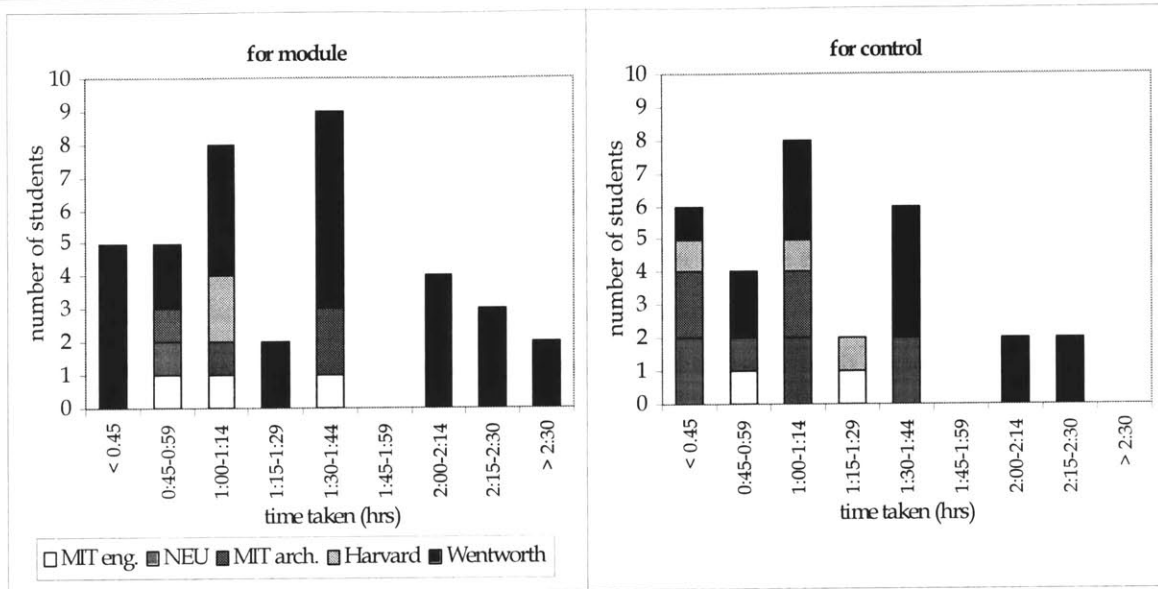
Figure 5.2   Times taken to complete the module/control

The first question on the survey was one of the most important and so its results are displayed below in figure 5.2 – How long did the module take to complete? The range was great with the most common length being between an hour and an hour and a half. This was slightly longer than was planned. Many of the Wentworth students, in particular, took much longer to complete the module or control than was anticipated. Additionally, on average, the students spent less time with the control. Due to its lower level of interactivity, this is no surprise. In the module, naturally the strong regulating of the student's progress caused the module group to have taken longer to complete it.

Further reinforcing these observations are the students' responses to the length of the module/control (figure D.1.2). Uniformly across the schools, there was a complaint of the module being too long with 59% of them indicating it longer than reasonable. The responses for the control were not quite so strong, but it was still considered longer than reasonable by 50% of the students.

The responses in figure D.1.1 for the question on the students' prior knowledge is the other set of results that should be highlighted. Across both groups of students, some of the responses did not reflect the expected judgment based on the number of previous classes the students had done. The NEU students, as the most experienced group of

students, marked themselves higher as is reasonable. However, a couple of the Wentworth students also went so far as to consider their prior knowledge excellent, which was clearly not the case that will be presented by the test results shortly.

The student responses for the other categories were very promising with the module gaining good ratings, particularly for the pace, interest level, relevance and, rewardingly, the animations. The help/feedback category also scored well. The only real problems identified with the format and content, was that the font size was sometimes too small and the text was considered by a few to be a little longwinded and unclear.

Many of the students also provided personal comments in the space that was provided on the survey forms. These often proved quite insightful and were encouraging of the learning approach and methodology. Here is just a small selection, identified by their ID number and school:

> "... pluses are: combinations of real images and drawings, matching force diagram and structural/architectural drawing symbol, ability to go back to certain images/definitions; and the minus is the using your knowledge section drags"   B505 (MIT arch.)

> "educational and interesting. Good interactive way to learn that is not boring."
>   M332 (Wentworth)

> "I liked to see re-life principles like the connections"   M526 (Wentworth)

> "very helpful to see reactions and forces in visual format"   B444 (Harvard)

> "can't fully understand in one module, needs time and repetition to sink in"
>   B510 (MIT arch.)

The last one is a particularly astute remark as it identifies what the control was lacking but what is at the heart of the module and methodology – an opportunity to engage and practice with a concept to help it "sink in".

Other comments were also helpful and are used in Section 5.4 as supporting evidence for the problems and issues that were observed with the module and evaluation.

5.3.4 Tests

Ideally, for a successful evaluation, when the post-test results are compared to the pre-test results for both the control and the module, a more marked improvement would be observed for the students who had completed the module. Unfortunately, this was not necessarily the case and the results were not clear-cut; the outcomes, however, still reveal some informative insights.

A rubric was necessary to grade and analyze the pre- and post-test results. This is presented in table 5.3. Each problem was broken down into its essential components and one point was assigned to each of these components. For the "multiple choice" type problems of questions 2, 3 and question 5 (test B only), applying this system is relatively straightforward. It was a little more challenging, however, for the other problems. This is particularly true for the reaction problems of question 4, where the approach finally adopted was to consider the calculation of each of the reaction forces, breaking it up into its components; i.e. check that (i) the reaction was shown on the diagram, (ii) the appropriate equation was applied properly to calculate it (i.e. $\Sigma F_v = 0$, $\Sigma F_h = 0$, $\Sigma M = 0$), (iii) the value was correctly found and (iv) the direction of the force was correct and in accordance with that shown on the diagram. One point was assigned to each of these components. Therefore, a problem with three reactions is worth a total of 12 points.

Comparing the results of the pre- and post-tests for the module and the control as just "total" scores was not informative, due to flaws in the test design and the disparity in the students' background and prior knowledge. Instead, the results are best examined by considering one at a time, each exercise and its testing purpose (as described in table 5.1).

Table 5.3   The rubric for grading the pre- and post-tests

question number	point structure	total points
1	1 point for each equation - horizontal forces - vertical forces - moment	3 points
2(i) (ii)	1 point for stable or not 1 point for determinate or not *or* 1 point for correct support arrangement	4 x 1 point 4 x 1 point
3(i) (ii)	1 point for stable or not 1 point for correct redundancy *or* 1 point for correct support arrangement	4 x 1 point 4 x 1 point
4	1 point for each of the four components for each reaction force on structure (including zero force reactions): - diagram - equation - value - direction	2 x 3-reaction problems for 12 points each 1 x 4-reaction problem for 16 points
5	1 point for correct deformation 2 points for reasoning, with one for comments about one side of structure and one for comments about the other side.	3 points
6 test A test B (i) + (ii) (iii)	1 point for correct force type in each element 1 point for yes/no 1 point for reason 1 point for correct sketch	2 x two-element problems for 2 points each, 1 x three-element problems for 3 points 2 x 2 points 1 point
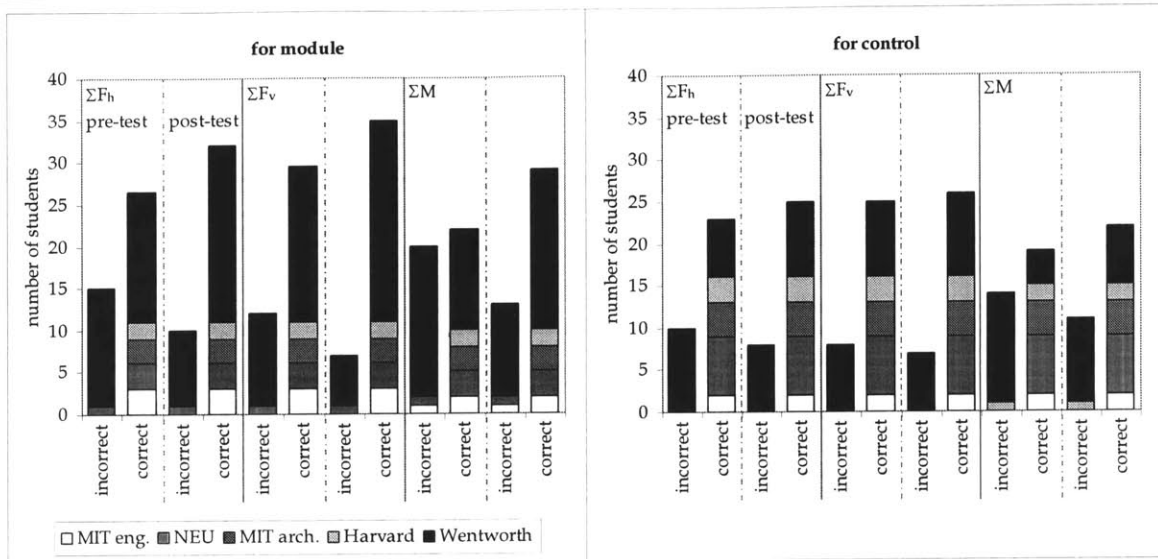
Figure 5.3   Number of students to get question 1 correct for the module/control

5.3.4.1 Question 1 – equations of equilibrium

Figure 5.3 presents the number of students who knew the equations of equilibrium, in both the pre- and post-tests, as histograms for the module and control. Recall this question was asked to check if the students had the prerequisite knowledge for engaging with the material effectively. The only students who did not perform well in the task were the Wentworth students; approximately half of them did not know the answer or left it blank. This foreshadows their poor performance in the following questions, in particular question 4, as they were clearly not prepared.

Furthermore, as expected there is little difference in the pre- and post-test scores, as the equations are not taught explicitly in the module/control, except for being presented once as "aside" information in a hyperlink.

5.3.4.2 Question 2 – stability of a single body

The first question to test directly the learning gained from the module/control, question 2 had two parts. The first asked if the body was stable. If it was, the second part asked whether it was determinate or not, while if it was not, the student was asked how to make it stable and determinate. There were four bodies to consider in the question.

Improvement ratios were calculated for each student based on the change in their performance from the pre-test question to the post-test question:

improvement ratio $=$ $\dfrac{\text{post-test score} - \text{pre-test score}}{\text{maximum score}}$

The two parts of the question were considered separately. (As there were four bodies, a student's maximum score for each part of the question was four.) The resulting ratios for the students are shown for the module and control in figures 5.4 and 5.5, respectively. The breakdown of the number of students who got each body and part of the question correct is available in figures D.2.1 to D.2.4 in Section 2 of Appendix D.

No marked statistical trends can be observed in the improvement ratios. Table 5.4 also demonstrates this by further summarizing the results by providing the percentages of students that performed both better and worse in the two parts of the question as well as presenting the average improvement ratio. Clearly and disappointingly, there is no correlation between the students' performances and whether they completed the

Table 5.4 **The percentages of students who perform better and worse, and the average improvement ratio for each part of question 2**

	module			control		
	worse	better	average ratio	worse	better	average ratio
part (i)						
MIT engineering	*33%**	33%	0%	50%	*50%*	13%
NEU	25%	25%	0%	*14%*	57%	11%
MIT architecture	33%	0%	-8%	50%	25%	-13%
Harvard	*0%*	50%	13%	33%	33%	17%
Wentworth	37%	40%	4%	*12%*	53%	15%
total	33%	36%	3%	*21%*	*48%*	11%
part (ii)						
MIT engineering	67%	33%	0%	*0%*	*50%*	19%
NEU	25%	0%	-6%	29%	43%	5%
MIT architecture	33%	*67%*	8%	25%	50%	6%
Harvard	0%	*100%*	25%	0%	33%	8%
Wentworth	27%	50%	14%	*18%*	53%	7%
total	29%	48%	11%	*18%*	48%	8%

**bold italicized* indicates the method to have the maximum improvement or minimum worsening.
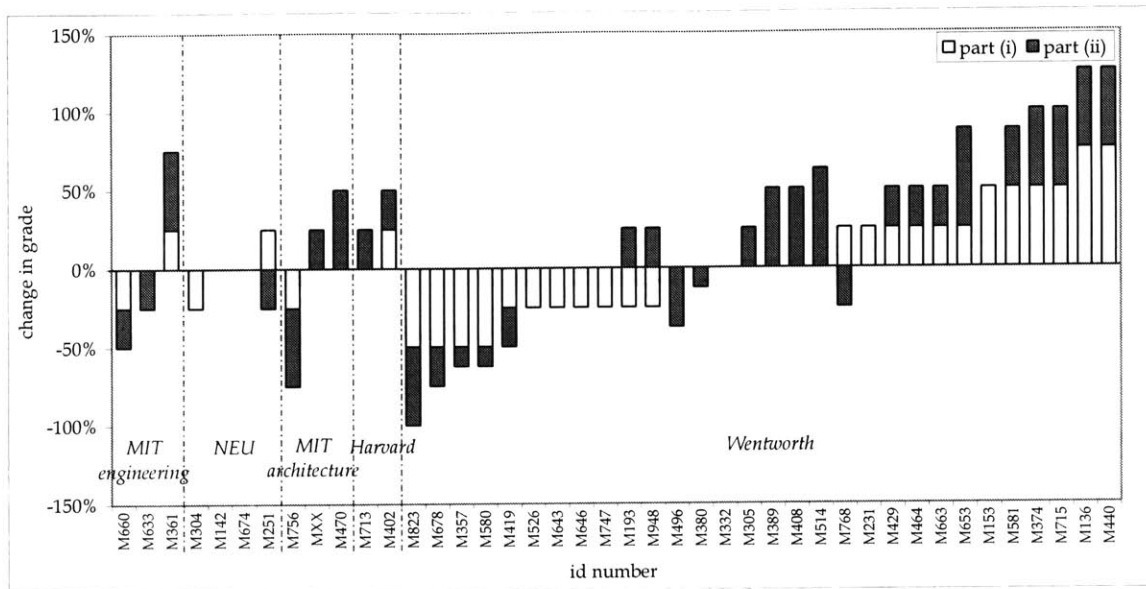
Figure 5.4   Improvement ratios on question 2 for the module
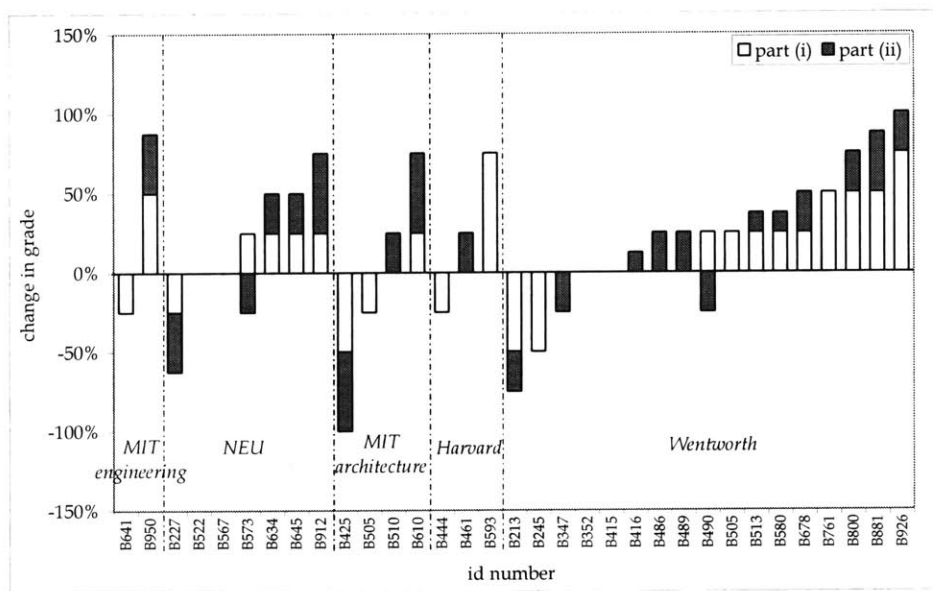
Figure 5.5   Improvement ratios on question 2 for the control

module or the control. Often there are just as many students who perform worse than who perform better. If anything, the students from the control group appear to have improved slightly more.

5.3.4.3 Question 3 – stability of an assembly

This question on the stability of assemblies tested the material covered by the later portion of the module/control. This is the portion of the module mentioned in Section 5.1, which did not undergo the same thorough preliminary testing as the rest of the module. Unfortunately, the material proved to be too challenging and confusing to the students. Supporting evidence for this is provided shortly, in Section 5.3.5.

The results for question 3 are presented in a similar manner to those for question 2; additionally, they too were poor. The two parts of the question are considered separately and there were four assemblies. This time the first part of the question asks if the assembly is stable or not. The second part, if stable, asks what was the level of redundancy and, if unstable, asks how to make it stable and determinate.

The improvement ratios are in figures 5.6 and 5.7. The detailed breakdown of the number of students who got each assembly and part of the question correct is available in figures D.22 to D.25 in Appendix D.2. Table 5.5 presents the summary of these changes as the percentages of students who perform better and worse on each part of the question, as well as the average improvement ratio for each part.

A small trend is seen with the performance of the module group typically being slightly better than that of the corresponding students in the control group. Furthermore, the engineering students gratifyingly performed much more respectably, particularly those who completed the module.

Regardless of this slight but promising observation, a greater issue is highlighted by how badly the students generally did perform, in particular those from Wentworth. Almost 60% of the Wentworth students from both the control and module groups did

worse in the post-test for part (i) of the problem. These students have either not covered the stability of assemblies previously in class, or if they have, then only poorly. More importantly, many of them complained in the surveys that they did not understand the last section of the module/control, finding it confusing and frustrating. The interaction results confirm this (c.f. Section 5.4). Therefore, it is clear that both the module and
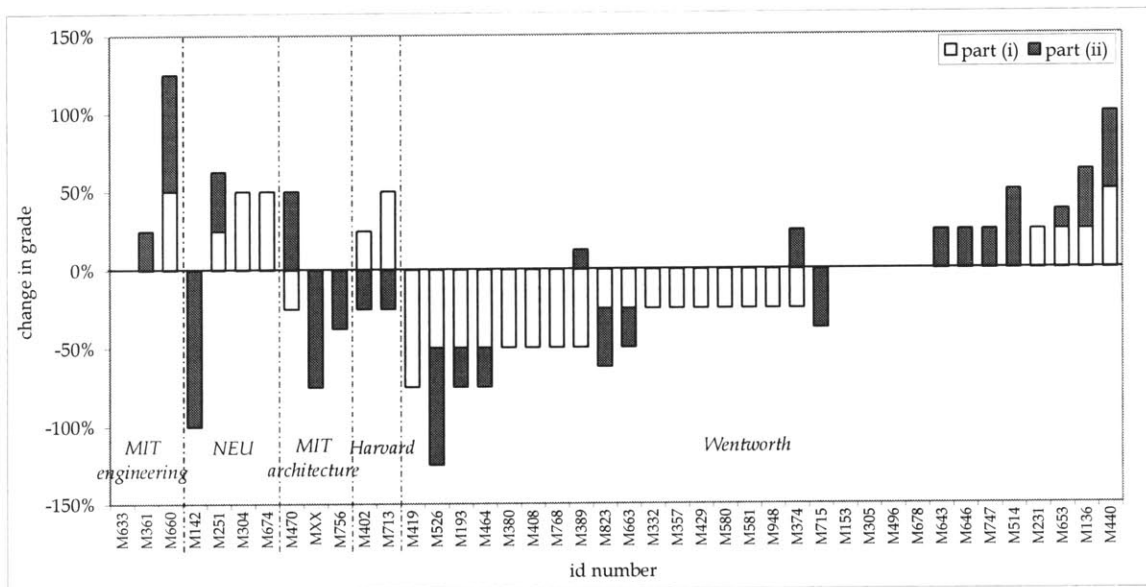
Figure 5.6   Improvement ratios on question 3 for the module
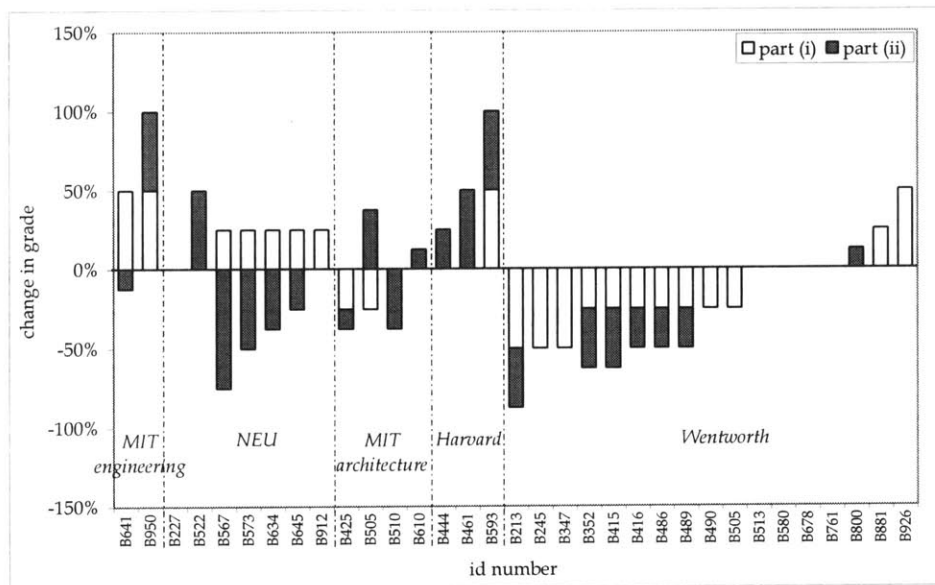
Figure 5.7   Improvement ratios on question 3 for the control

Table 5.5 The percentages of students who perform better and worse, and the average improvement ratio for each part of question 3

	module			control		
	worse	better	average ratio	worse	better	average ratio
part (i)						
MIT engineering	0%	33%	17%	0%	*100%**	50%
NEU	0%	*75%*	31%	0%	71%	18%
MIT architecture	*33%*	0%	-8%	50%	0%	-13%
Harvard	0%	*100%*	38%	0%	33%	17%
Wentworth	57%	13%	-18%	59%	12%	-15%
total	43%	24%	-7%	*36%*	*30%*	-1%
part (ii)						
MIT engineering	*0%*	*67%*	33%	50%	50%	19%
NEU	25%	25%	-16%	57%	14%	-20%
MIT architecture	67%	33%	-21%	*50%*	*50%*	0%
Harvard	100%	0%	-25%	*0%*	*100%*	42%
Wentworth	20%	*30%*	1%	35%	6%	-10%
total	26%	*31%*	-1%	39%	24%	-5%

*bold italicized indicates the method to have the maximum improvement or minimum worsening.

control failed in teaching this section properly, with the module doing only a slightly better job.

As an aside, it should also be observed that the test order may have had an effect on some of these poor performances, especially for part (i) of the question, as the Wentworth and MIT architecture students were the only ones to have been given test order B-A. The students from these two schools performed particularly poorly, with the only negative average improvement ratios in both the control and the module, thus reflecting an unintentional bias in the test design. Even so, however, comparing the results for the module and control groups, the performance by the module students is still slightly better.

5.3.4.4 Question 4 – calculating the reactions

Question 4, calculating the reactions, was designed to test, through a performance assessment, for any enhancement to the students' understanding of the classroom material. It does not test the module material directly. To help analyze for this

enhancement, therefore, the improvement ratios are prepared in two different manners. Firstly, figures 5.8 and 5.9 present the ratios for the module and control respectively by considering each problem in the question: a) the cantilever beam, b) the frame and, c) the structure with an internal hinge. The second set of ratios provided in figures 5.10 and 5.11 present the ratios broken down into the conceptual components of the problems, as described in the grading rubric: the equation, value, direction and
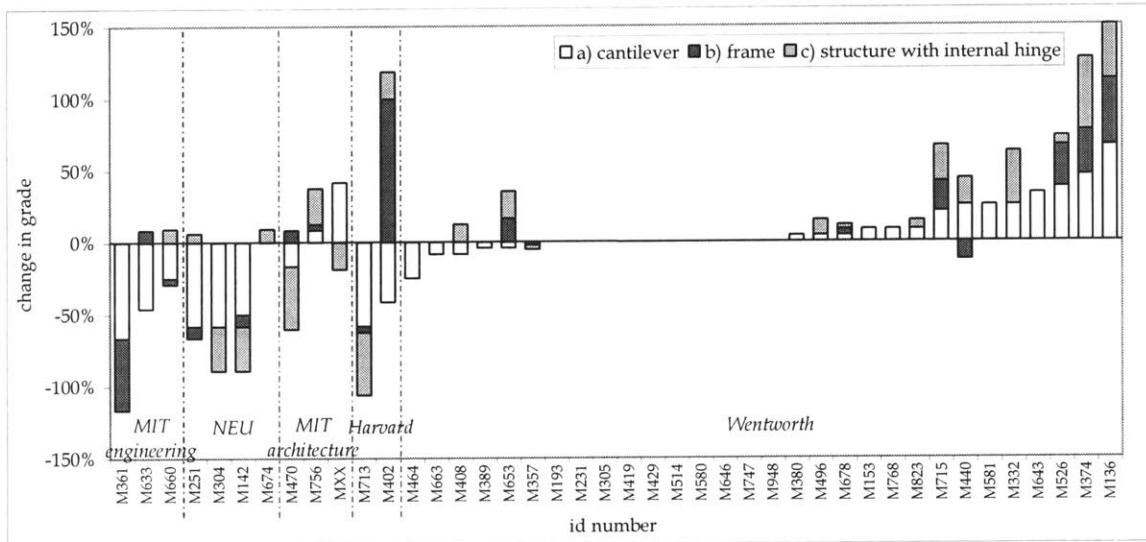
Figure 5.8   **Improvement ratios on question 4 by "problem" for the module**
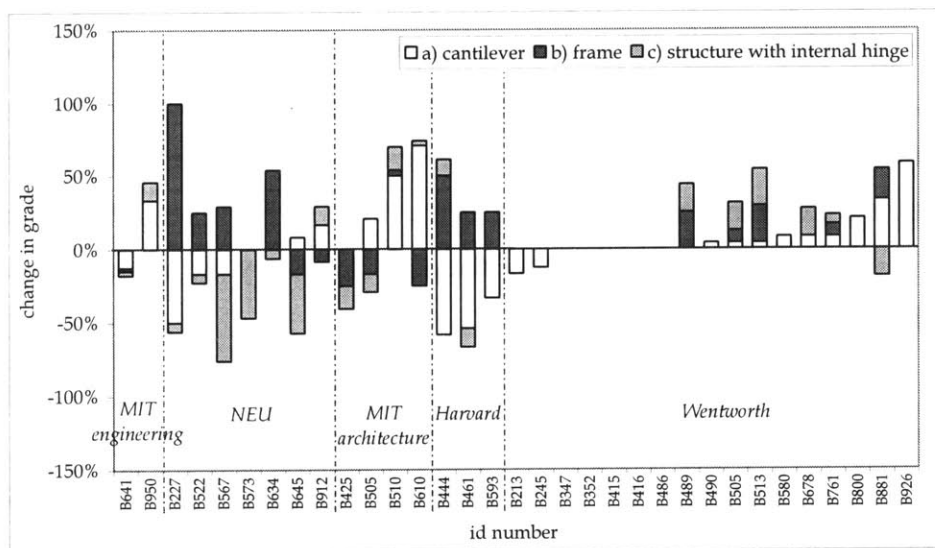
Figure 5.9   **Improvement ratios on question 4 by "problem" for the control**
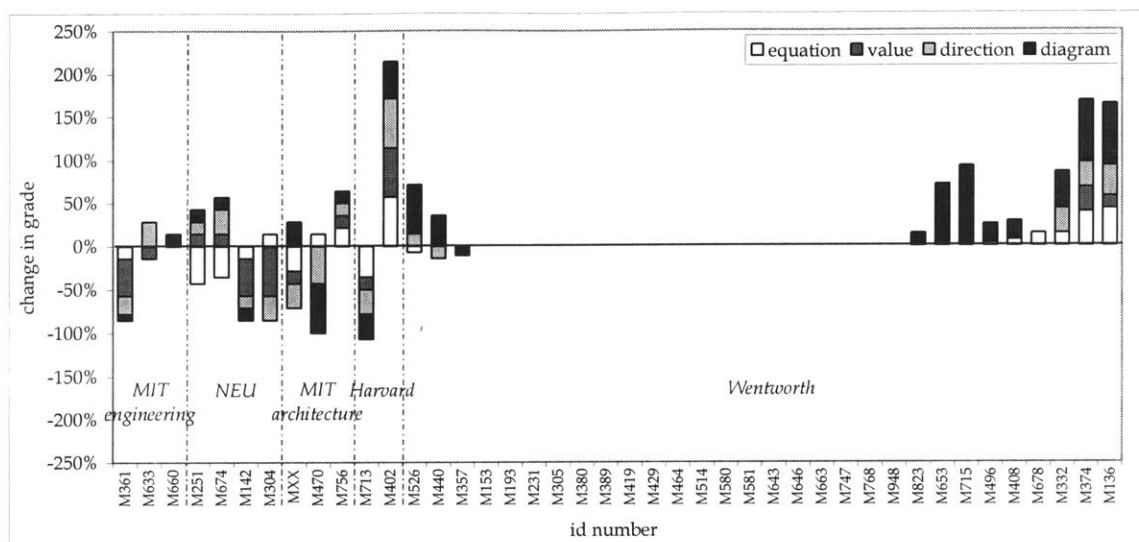
Figure 5.10   Improvement ratios on question 4 by "component" for the module
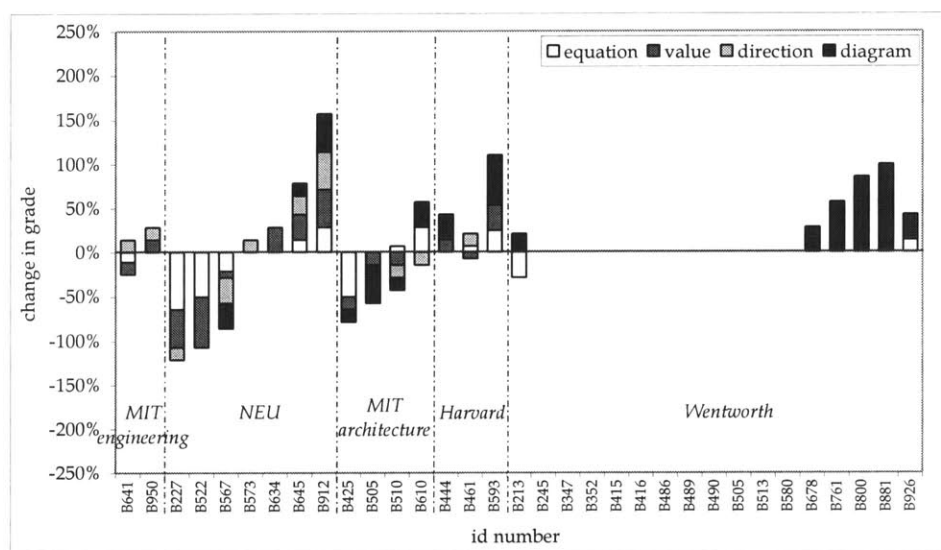
Figure 5.11   Improvement ratios on question 4 by "component" for the control

diagram. Only the second and third problems are included in this set. The reason why is explained shortly.

The patterns observed in these results vary greatly with the school and discipline of the students. As anticipated by their not knowing the equations of equilibrium, many of the Wentworth students did not know how to do these reaction problems, so left them blank. Therefore, the purpose of this question for these students is largely defeated. There are some positive outcomes, however, as in the post-test the Wentworth students

did apply what they had gained from the module/control and at least indicated the reaction forces on the diagram. Hence, their most noticeable improvement is seen in their marking of the FBD correctly. The students from both the module and control groups demonstrate this improvement, though more so the module group.

Recall that the main reason for providing the cantilever problems at the beginning of this question was to make the students comfortable with an "easy" problem. Unfortunately, the cantilevers were not fully successful in this, showing an oversight in the test design. The students with the test order B-A (MIT eng., NEU and Harvard) performed poorly in the post-test cantilever problem, because this problem involved a beam with an applied moment load. The moment load is often more challenging conceptually for elementary students to handle and so caused them to perform more poorly in this problem compared with the much simpler cantilever problem in Test B. It only has with an applied vertical end load to deal with. Thus, almost all of the B-A students displayed negative improvement ratios, and conversely the other students achieved a positive ratio.

Furthermore, if the students did know how to deal with the moment load, they often only indicated the moment reaction, ignoring the horizontal and vertical reactions, as they are zero forces. The grading rubric, however, was setup to require these to be marked as well (an essential aspect of the module's teaching is to consider the loads/reactions in all directions). Hence, these students also achieved a poor grade for this cantilever problem. Therefore, the results comparing the two cantilever problems tend to be skewed and erroneous. This is why the ratios by "components" in figures 5.10 and 5.11 are calculated for the second and third problems only.

Unfortunately, no other trends in the results are discernable. For completeness' sake, Table D.2.1 of Appendix D.2 provides the percentages of students who performed both better and worse for each conceptual component of the problems in question 4.

5.3.4.5 Question 5 – predicting the deformation of a structure

For question 5, a conceptual test, not much can be read from the results at all; almost everyone performed badly in both the pre- and post-tests. Figures 5.12 and 5.13 present the individual grades for these tests for the module and control, respectively. The pre-test grades are plotted on the positive y-axis and the post-test ones are on the negative axis. The maximum score was three. The post-test grades were particularly bad, and there was certainly little difference between the results for the module and the control groups. Perhaps the students did particularly poorly in the post-test, as they were tired or apathetic. This question was a qualitative problem, requiring the students to articulate the concepts – one of the skills that is recognized as poor in structures students. Thus, it is quite possible through frustration and tiredness, etc that the students could not be bothered.

Nevertheless, these poor results, in general, were due to another flaw in the test design, as unfortunately it is now apparent that the question was too advanced, requiring an understanding of elastic deformation and compatibility. The students had not yet developed the intuitive understanding to answer it.

The only good observation that can be made from these results is with regards the grades of the engineering students. The NEU students were the most advanced students of the group, yet their performance was mediocre. The MIT engineering students, who recall fit the target audience the best and are of an elementary level, performed much better, however. This could well be owed to the strong conceptual teaching approaches of Prof. L. Bucciarelli, which were referred to in Chapter 2.
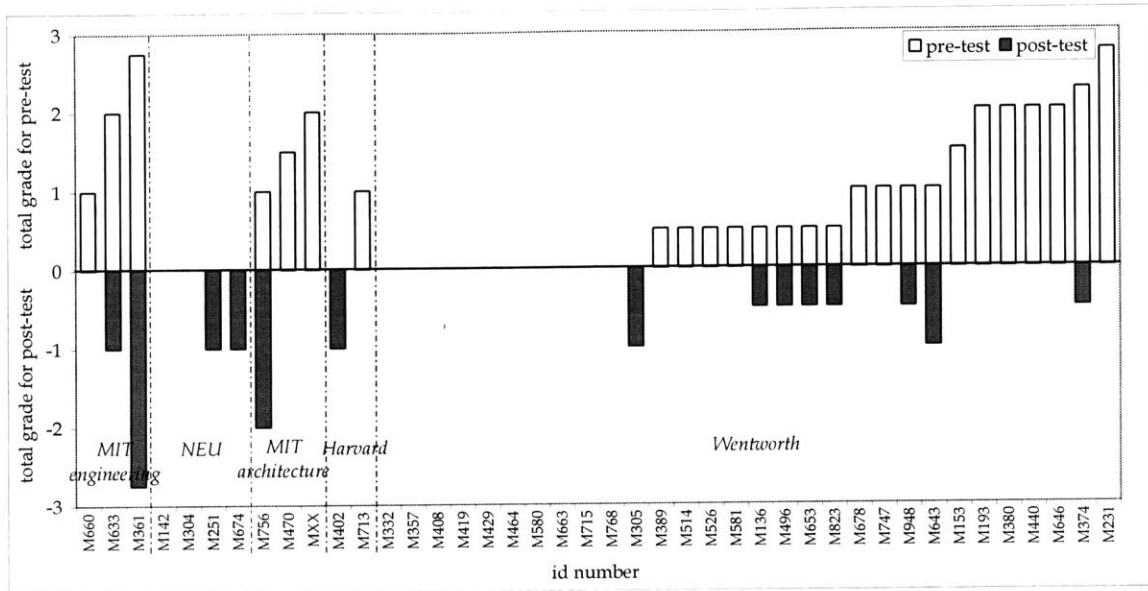
Figure 5.12   The individual grades from question 5 of the pre- and post-tests for the module
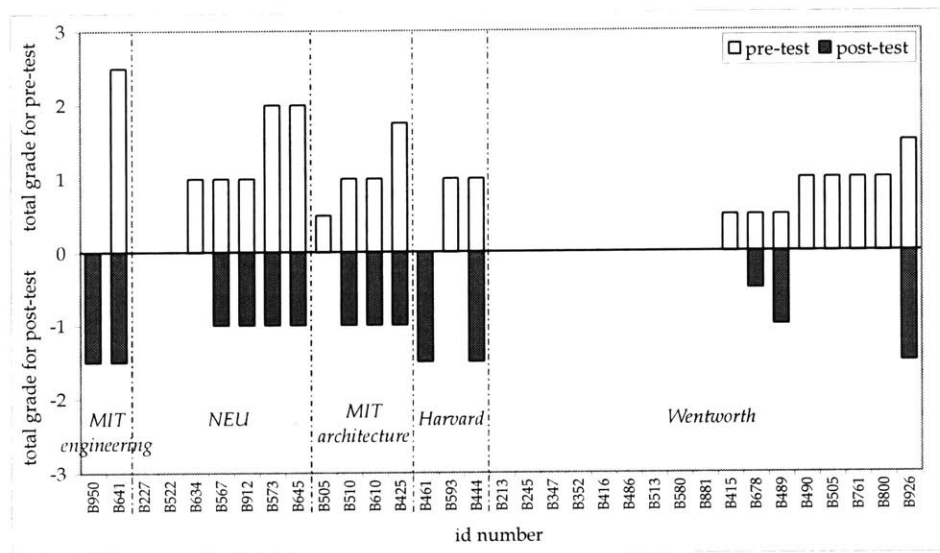
Figure 5.13   The individual grades from question 5 of the pre- and post-tests for the control

5.3.4.6 Question 6 – Test A: tension/compression in structures
Test B: stability of a 3D frame

Question 6 in each of the two tests, although different, was of very similar difficulty and tested for understanding of many of the same skills. Therefore, comparing the results of the pre- and post-test is quite acceptable; figures 5.14 and 5.15 display the improvement ratios. The individual grades for both the pre- and post-tests for the module and control are given in figures D.2.9 and D.2.10 in Appendix D.
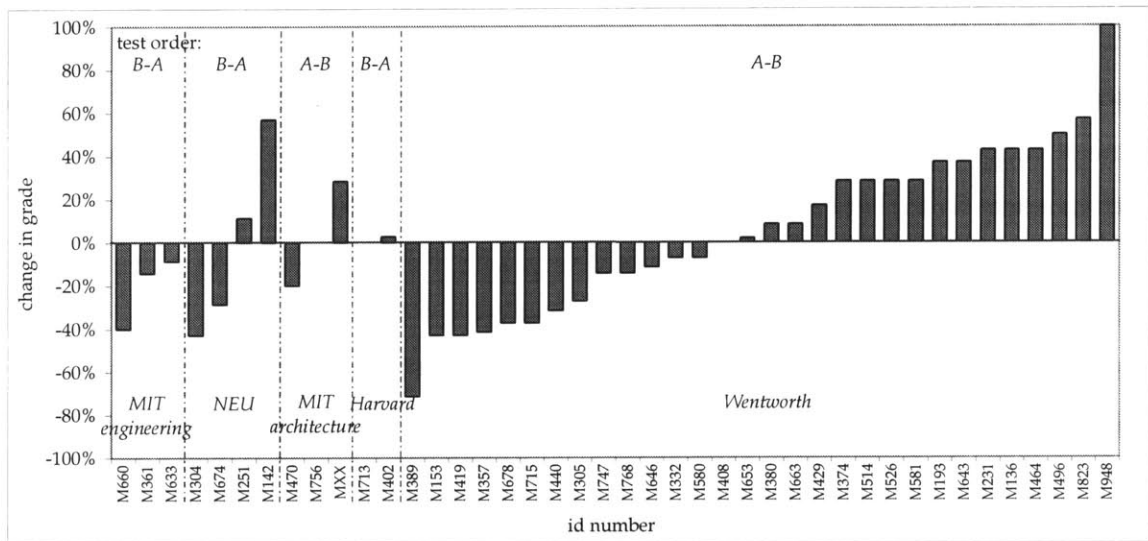
Figure 5.14   **Improvement ratios on question 6 for the module**
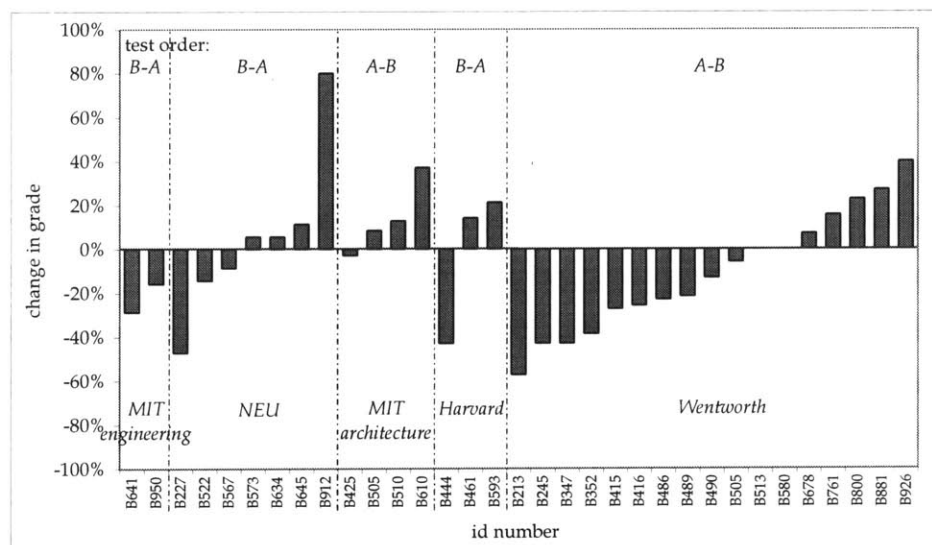
Figure 5.15   **Improvement ratios on question 6 for the control**

The students performed much better with this question. Across the board, they gained good results in both the pre- and post-test. Consequentially, the improvement ratios show no statistical trends across any of the schools. Hence, although the students performed poorly in question 5, they managed to do well in question 6, which was testing similar skills, although more basic. Recalling from table 5.1, these skills included the ability to achieve a conceptual knowledge of geometric compatibility and to follow and identify load paths.

5.3.4.7 Summary of test results

Question 1 demonstrated that the Wentworth students were the only ones not to know some of the prerequisite knowledge for doing the module. This foreshadowed poor performances from these students in many of the other questions.

Disappointingly, in question 2, there was no marked difference between the students' performances in the module and the control. The results for Question 3 were only slightly better with the module group showing a slightly better improvement over the control group. The engineering students, in particular, performed better. The greater issue with this question, however, was the discovery that the last portion (assemblies) of the control/module was too complex and confusing to the students, thus failing to teach the students the topic necessary to answer the question properly. The module group did slightly better though, perhaps indicating that the interactivity made it a little clearer.

The results for question 4 were difficult to make clear observations on, as there was a great variation between the schools and discipline of the students. In general, the Wentworth students did not how to do the problems, but they did show a good improvement in their abilities to label the free-body diagrams, reflecting what they learnt in the module/control. The module group performed better in this. Unfortunately, no other trends were discernable in the results. The only other outcome from this question was the identifying of a flaw in the first problem of Test A. The cantilever beam with an applied moment load caused skewed results, as it was realized

to be more complex than the corresponding problem in Test B.

Question 5 was shown to be too advanced for the audience; therefore, the test results were uninformative. Lastly, from question 6, again there were no visible trends, however, the students did perform much better on it than with question 5.

Thus, the findings from the test results tend to be meager, due to (i) the test audience being somewhat off target and (ii) the last section of the module/control on assemblies being too complex. Through this, however, there are still some small promising indications of the module's effectiveness and better performance over the control.

5.3.5   Module Interactions

5.3.5.1 Results

The interaction data was only collected from the students who completed the module. Recall, the control has no interaction capabilities as that is its main difference from the module. Therefore, no data was available for the control group.

Not all of the students who completed the evaluation packages managed to successfully submit their interaction data. However, a collection rate of 73% was achieved, which is very respectable. Additionally, there was data for two extra students, who were unidentified, bringing the total to 32 students. A full profile of the students is contained in Table 5.6.

The data collected for each student was the number of attempts they made on each exercise and if they got it correct or not before continuing. As can be imagined, this data was quite copious and became somewhat challenging to deal with. First, the results for each exercise were simply analyzed and summarized. Then, potential correlations were explored between the students' performances in the module and their test grades.

Table 5.6 **The number of students and their background whose interaction results were successfully collected**

school and discipline	module			% of those who did test	year (typically)	typical number of previous Structures classes
	male	female	total			
civil engineering:						
MIT	1	2	3	100%	sophomore	0
NEU	3	0	3	60%	junior	2
architecture:						
MIT	2	0	2	66%	graduate (y2)	1
Harvard GSD	1	1	2	100%	graduate (y1)	0-1
Wentworth	11	9	20	64%	sophomore	0
unknown			2			
total	18	12	32	73%		

Considering the analysis for each exercise, the best representation for each was to summarize its data through two histograms. Each is a plot of the number of students versus the number of attempts. The first has this information broken into the schools and disciplines of the student, while the second simply breaks it down into whether they got it correct or not. Note, for some of the simpler problems, the student was allowed only one attempt, so only the second histogram was needed, or alternatively they were not allowed to move on unless they got the exercise correct, so then only the first histogram was necessary. The resulting plots with accompanying descriptions of the exercises are in Section 3 of Appendix D.

However, there are two exceptions to this format of summarizing the data. The first is the beam exercise simulation explained in detail in Chapter 4 (c.f. Section 4.1.15.1), and the second is the review exercise that asks the student to make stable and determinate a given body that has been randomly oriented and supported. It brings together the work of the previous exercises on restraint types and the rules of determinacy and stability. Both of these interactive exercises have (i) adopted simulations and (ii) are repeatable. The student was asked to complete them a minimum number of times and then she was free to move on or stay and practice for longer. Furthermore, each time the student did the exercise she was required to complete the task correctly. Therefore, the data cannot

be simply summarized in the aforementioned histograms. Instead, the histograms were organized to present the students' results individually.

For the beam exercise, the data collected also told us whether the student found a determinate or indeterminate arrangement. The resulting histograms, in figures D.3.3 and D.3.4, plot the number of arrangements each student completed against her ID number. Figure D.3.3 breaks this information into whether it was a determinate or indeterminate arrangement she found, while figure D.3.4 is broken down into the number of attempts each arrangement took to get it right. Additionally, these breakdowns are presented for each student in the order in which she developed the arrangements, going from the bottom upwards in the "bar".

Recall that before moving on in the module, the student was required to make at least three stable arrangements with at least the last one being determinate. Please note, to make more apparent the performance patterns, the order of the students along the x-axis is sorted within each school by the number of arrangements the student found.

For the review exercise, the student was required to consider at least three different bodies, making them stable and determinate. Some students made many attempts and a good portion considered more than the required three bodies. Therefore, to present this clearly, the histogram in figure D.3.15 plots the number of times the problem was completed against the ID number, breaking these results down into the number of attempts that the student made on each. Again, the student order along the x-axis is sorted within each school by the number of times the student completed the problem.

For completeness, tables summarizing the students' individual marks and attempts for every interaction exercise are also provided in Appendix D, Section 3 in tables D.3.1 and D.3.4.

5.3.5.2 Observations

Examining the various graphs, some interesting observations are made of the students' behavior. Firstly, considering the first two thirds of the exercises (those up to the introduction of assemblies) in figures D.3.1 to D.3.16, they all demonstrate a good level of challenge and engagement. Not one of the exercises required just one attempt by everyone to get it correct; most, however, were answered within the second attempt. It was good to see for instance that the first exercise – the rigid body motion problem discussed in Chapter 4 – took most students two attempts, figure D.3.1. Additionally, an encouragingly large number of the students persist beyond the required two attempts until they succeed in answering the problem correctly themselves, for instance with the rigid body motion problem, the persistence rate was 60%. Perhaps, this reflects not just the tenacity of the students but also the positive success of the module to retain the student's attention and help her work through the problem.

The outcomes of some of the individual exercises provide further insight. For instance, the results of the beam exercise in figures D.3.3 and D.3.4, as previously introduced, shows that 34% of the students did more than was required of them. The more experienced students at MIT architecture and NEU consistently chose determinate arrangements, even before being asked to, while the Wentworth students certainly did not, indicating inexperience in the concept.

Carrying this observation through it is interesting to see how it reflects on the results of the next set of exercises in the module (figure D.3.5). Recall from Chapter 4, these problems are designed as follow-on exercises, presenting various beam arrangements and asking whether they are stable or not. The students clearly perform well in recognizing the first one (b1a) as unstable and the second one (b2) as stable. The last two problems, however, are trickier and caught up many of the students, regardless of their experience. This is understandable for the inexperienced students, as at first glance, the unstable beam, b3a, appears to be determinate. Therefore, perhaps the students who found only determinate arrangements in the beam exercise fell into the module's "trap" by not having explored the full possibility and potential tricks of

stability. Similarly, the students had difficulties with beam b4, which presents coupled end restraints as an introduction to the discussion on fixed end (moment) supports that occurs a little later in the module.

The other results presented in this graph of figure D.3.5 are the second part of the exercise for the unstable arrangements. Demonstrated by the students' poor performance, the requirements of these tasks (b1b and b3b) were moderately confusing or unclear (the students were to indicate which point the beam is likely to rotate about as it fails). For instance, the students performed better in b3b, perhaps indicating the students found the task unclear when first given it for b1b, but they then learnt from it and improved in b3b. Either way, it is felt that the extra concept being taught through this part of the exercise did more harm than good and was proved unnecessary to the overall learning goals and discovery path of the module.

Returning to figure D.3.15, introduced earlier, to examine the results of the review exercise, 66% of the students continued practicing the task beyond the required three times. However, 53% had to make more than three attempts to get at least one of their bodies correct. With the Wentworth students, this proportion went as high as 65%, indicating this exercise may have been slightly too challenging and in turn frustrating for some of the students from the more elementary end. More importantly, it proves that because the students were so elementary, as reinforced by their poor performance in the first question of the evaluation tests, much of the material being covered is new to them – newer than anticipated for the target audience. Perhaps more effort needs to be made to ensure these individuals practice the earlier concepts of the module and consolidate their learning further. Comparing this outcome to the other schools, their students performed much better, with the well experienced NEU students having very few problems and the MIT engineering students, who best represented the target audience, engaging with the task properly and as anticipated.

The task covered by the review exercise is one of the few that directly related to one of the questions on the evaluation tests – question 2. Therefore, it is interesting to compare

the improvement ratios of the individual students for this question to their corresponding interaction results taken from the graph in figure D.3.15. The two graphs are combined to include only those students who successfully submitted their interaction data and completed the tests. The result is presented in figure 5.16 with the corresponding ID numbers. The most exciting outcome from this comparison is the clear observation that the students who practiced the task more than necessary performed better in the post-test. This was particularly true for MIT engineering, Harvard and Wentworth for whom the concept of a determinate structure was much newer. Thus, it would appear to indicate the effort of engagement with the phenomena is worthwhile, recommending the more efforts made to encourage and actually enforce the student to interact, the better.
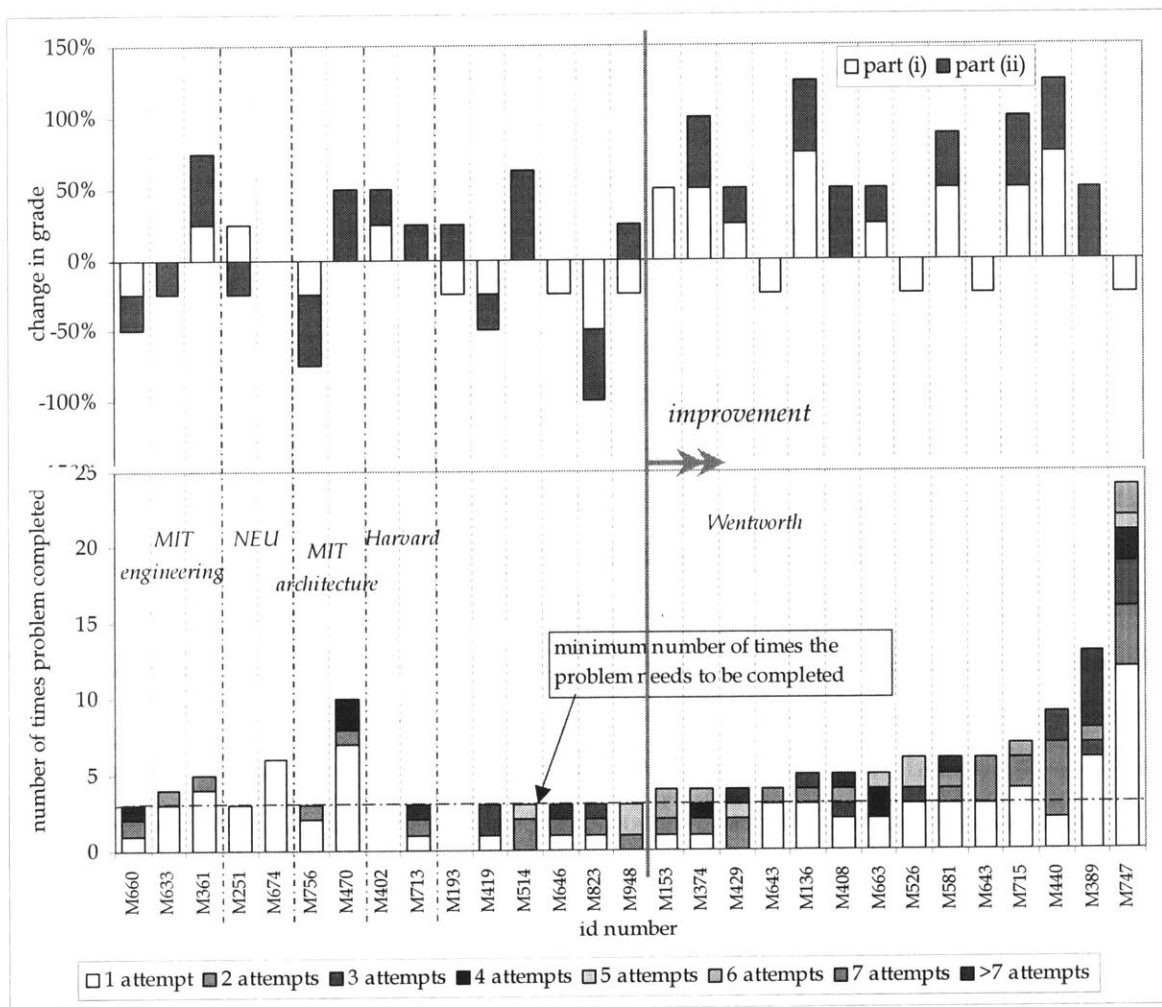
Figure 5.16 **Comparison of the improvement ratios and corresponding interaction results for the question 2, for each student**

This is the only cross-comparison made between the interaction results and the test results, as, as stated, it is one of the few problems that the relationship could be easily and directly made between the two sets of results. One other potential cross-comparison could have been made between the results of the assembly exercises and the grades from question 3, which was on the stability of assemblies. Unfortunately, however, the efforts of teaching this material in the later portion of the module were clearly unsatisfactory, so any further analysis of these results beyond presenting figures D.3.17 to D.3.26 is wasted. Additionally, it is already known that the students' improvement ratios for question 3 were poor.

Examining figures D.3.17 and D.3.18 for the first assembly exercise, the students were undoubtedly confused and gave up in frustration, often after many attempts. By the second assembly, the students were no clearer and they no longer bothered to make many attempts to struggle through and work it out. Clearly, the module lost them and failed to get them back on board and into the correct thought process. The students who did make it through reasonably were those of more experience, like the NEU and MIT architecture students, as well as, encouragingly, the engineers at MIT.

In conclusion, from the level of analysis on the module's interaction data presented here, there are three interesting insights provided. Firstly, as a whole (and excluding the assembly section) the interactive exercises were demonstrated to properly engage the student with stimulating experiences. Second, it was positive to see the high level of persistence the students displayed, reflecting the success of the module to absorb and assist the student. Furthermore, this persistence reflected in better test scores. On a more disappointing note, the last lesson proved the module's section on assemblies to be too confusing and challenging. The students' frustrations revealed the module had been over-ambitious.

5.4   Further Observations

The analysis of the interaction data could continue in detail, making more efforts to investigate for connections between the students' engagement with the module and the test results. Scenarios to explore include: Do the students' efforts improve through the module – i.e. less attempts made with time spent on related material? How do the students' comments on the surveys reflect on the test scores and interaction issues? And, what about the judgment the students gave on their grades in the surveys? Did the students who considered themselves "poor" show a better or worse improvement? Does gender make a difference?

Before launching into such efforts, however, it is important to remember the quality of the data collected. The students tested had a great diversity and unfortunately, the test pool at each school was, statistically, very small. Wentworth was an exception to this; however, the flaw with these students with respect to the evaluations, was that they were a little below the standard of the target audience, appearing to lack some of the prerequisite knowledge. Therefore, for all of the students, greater levels of analysis are unwarranted and could be statistically misleading. Instead, combining the observations from the three areas of results – the surveys, tests and interactions –previously introduced provides more than enough lessons to inform worthy future work and assessment. These lessons and conclusions are examined in the following subsections, with further supporting evidence from the students' comments taken from their surveys. .

5.4.1   The length of the module

Without a doubt, the length of the module had the greatest impact on the results. As explained at the beginning of this chapter, it was made longer than the ideal length so as to provide a larger learning experience, which the student was well immersed in and could make an informative evaluation on. Although with these best intentions, the efforts were defeated and the resulting module was too long as many of the students indicated in figure D.1.2; *"my mind wandered"* (M193 Wentworth). Unfortunately, this

affected the learning impact of the module and if anything undermined what the students were learning by tiring them with too much information. This would obviously influence their exam performance.

> *"very good module, very clear and understandable. However, when I finished and took the test for a second time I had forgotten some of the information and was again confused. Too much information to obtain in one session."*
>
> M374 (Wentworth)

Furthermore, the fact that many of the students also had to install the Shockwave plugin to view the sight would have eroded the students' enthusiasm, tiring them even further.

> *"the Shockwave player was a pain to install"* B926 (Wentworth)
>
> *"it was well done but I had problems downloading Shockwave"*
>
> M408 (Wentworth)

The cause of this problem of the module's length breaks down into two further issues. One was obviously the desire to make the single learning experience to be of impact, but the other was the module's level of complexity.

5.4.2 The complexity of the module

The dilemma when developing the prototype was to choose a topic that was relatively easy and did not require too much prerequisite knowledge yet was still relevant and engaging. Therefore, concerned that some of the earlier concepts in *"rigid body stability"* were a little too simple, the section on the assembly of elements was included at the end of the module. It completed the discovery path of "divide and conquer", taking the module from single elements at the beginning to the end where the pieces are brought back together. Furthermore, it made the design of the evaluation tests easier; if only single bodies and supports had been covered, it would have been too elementary to design a good set of questions used to test for enhancement of the classroom knowledge.

Unfortunately, this decision revealed the module to be over ambitious, because even though this section was thought to be presented clearly, it was actually shown to be too complex. Thus, on top of the length problem, caused confusion and frustration:

"...the last couple of sections were confusing..."   M304 (NEU)

"...too hard at end"   M756 (MIT arch.)

"the end was really hard"   M646 (Wentworth)

This obviously works to further weaken the learning impact of the whole module.

The conclusion is to never assume something is too easy, and more importantly, it reflects how significant it is to know your audience and what their learning needs are.

5.4.3   Unsatisfactory amount of informative feedback for "assemblies"

Although, the assembly section of the module was too complex for the students, the cause was not just the topic itself, but also flaws in the interactive guidance and feedback that the module provides for it.

A lot of work was put into crafting the animations to present the assemblies, explain the concept and demonstrate what was required for the interactive aspects, but it was to a mixed success according to B425 (MIT arch.):

> *"the part of the module when pieces were brought to the whole was not explained well. Everything else was though. I really understood the stability of the items with one member, but when the module began to analyze multiple-member structures I was very lost. I did not understand all the arrows...."*

Admittedly, this was from someone in the control group. However, M756 (MIT arch.) also complained:

> *"the actual technique of decomposition and analysis was not clearly explained. I still don't understand it... It was really frustrating not to be able to get a slower more thorough explanation of how to do it. I gave up."*

The real problem however was in the feedback. It is now apparent that this section of the module did not succeed in ensuring informative and specific feedback to the student's problems, nearly as well as the rest of the module.

> *"....Basically I thought it was great until I got stuck and there wasn't enough depth of explanation to clarify how to do the problems... ...(and with the last section) the help didn't help with the technique, only with your answer. It also only applied to your last submitted response."*   M756 (MIT arch.)

The interaction results also support this evidence of the module not catering sufficiently

to the students' needs so as to help work with them through the material. Due to the complexity of the simulation exercise with its greater number of possible errors, it was much more challenging to narrow down the student's problem and provide pertinent guidance to it. During the module's design, it was felt that a satisfactory experience had been achieved, but obviously not. This lack of adequate feedback and guidance for the one section is a flaw in the module, but not the methodology. This finding simply indicates a section where the requirements of the methodology have not been followed correctly.

This one point of failure does have an insightful flipside however, as is it helps to further highlight the success of the rest of the module at supporting the students through the material and keeping them engaged...

> *"the beginning was good I felt I learned a lot, but the middle and end got too hard. I had no clue what I was doing so it took me forever and was frustrating... to make this an excellent tool...make everything as clear as the beginning"*
>
> M646 (Wentworth)

5.4.4   The challenge of reaching the right students to do the evaluation

As has already been highlighted, in Section 5.3.2, a major challenge with the evaluation of this research was gaining access to students from the target audience to test the module. Even with the evaluation process being designed to be of minimal interference to the instructor, there was the challenge of having it accepted within the cultures of the different universities and instructors.

Although, somewhat successful in reaching a variety of students with this evaluation, many did not fit the profile of the target audience perfectly. The largest group of students (63%) were from Wentworth and they appeared to be slightly too elementary and so have skewed the results somewhat. The students from the other schools showed a good mix and diversity, however, the test pool from each is small with typically 2 to 3 students in each of the control and module groups, which is statistically weak for observing trends.

Getting an audience that is not true to the target audience can be misleading, not to mention frustrating, particularly when interpreting the results to the exam questions. For instance, typically, the Wentworth students did not know how to do question 4, the calculation of reactions question, on the tests, which was a large portion of the exam. Therefore, the means of gaining feedback on their learning is substantially reduced.

5.4.5   The effect of being a one-time experience

The students did recognize that the module *"took the necessary time to cover the material"* (M633, MIT eng.) when commenting on its length, but the problem still lies in trying to cram too much into a one-time experience. Clearly, the methodology would be better tested if the impact were measured progressively through multiple modules of a more sensible length. Assigning the module to the students as a real part of their learning experience and not just as a try-out should present much more effective and realistic results. This approach requires a well-controlled and reasonable sized test bed of students, however. Unfortunately, MIT CEE has only a small group of undergraduate students each year (approx. 10). Furthermore, MIT students are unlikely to provide the diversity of ability that is desirable. Therefore, this research relied on volunteers from a range of schools for the evaluation.

The students were certainly receptive to the idea of being able to *"save and come back"* (M514, Wentworth), and *"breaking it up into two parts to do at different times"* (M526, Wentworth) or *"split*(ting) *it up into separate more in-depth modules"* (B641, MIT eng.). With the module and the problems previously discussed, the ideal point to cut it would be just before the assembly section. For instance, the discovery path could then be satisfactory closed by some strong closing remarks that could set up for the "next module" containing a enhanced version of the assembly material.

5.5   Conclusions

With respect to the evaluation criteria outlined in Section 5.2, the methodology was not proven outright to be effective. The indicators were positive however, and the results were not shown to be from any fault in the methodology, but instead due to issues with the evaluation process and the module.

Education tools are often developed and adopted for the sake of the technology and the well-meaning desire to provide new means of transferring knowledge. This is particularly popular with engineering professors due to their enjoyment of tinkering with new technologies. Unfortunately, however, the time and effort is not usually available to rigorously assess their effectiveness, instead gut feelings are relied on. Therefore, the discipline of carrying out good evaluation in engineering education is still limited, and one of the biggest successes of the evaluation efforts described in this chapter is the experience gained from actually carrying the process out in a practical manner.

Section 5.4 highlighted some cautionary concerns with this evaluation process; they include reaching the appropriate audience and testing the methodology through a one-time experience. In Section 5.3.4, problems were also revealed with some of the test questions. The question assessing the student's skills directly related to the module worked well. The other questions, checking for enhancement to the student's classroom knowledge were not always so successful, however. They were challenging questions to pose, because a good knowledge is needed of the audience to be confident the questions are appropriate and informative, yet the audience is inherently diverse due to the different institutions and disciplines participating.

The other issues outlined in Section 5.4, were concerning the module, i.e. its length and complexity. All of which had a great impact on the test results and how they should be interpreted.

Beyond these setbacks and flaws in the evaluation however, positive results are still revealed about the methodology. The students' responses in the surveys to the new teaching mode were very encouraging. The analysis of their interactions and test results (particularly question 2) demonstrated that the approach of the methodology to engage the student and draw them through a problem was successful. Thus, indicating the more efforts made to encourage and actually enforce the student to interact, the better. Lastly, even though the last section of the module on assemblies failed, this was shown to be because it did not satisfy the methodology. Therefore, it indirectly works towards further highlighting the success of methodology.

In conclusion, through this research, the need for such a learning approach to teach conceptual material was demonstrated, and that in itself is reward enough for the efforts made here.

Future evaluations, once successfully carried out will provide a rich source for examining learning behavior, allowing the opportunity to explore the influence of such things as diversity of discipline (architect vs. engineers), experience (institutions and backgrounds) maturity (undergraduates vs. graduate students), gender and learning styles.

Chapter 6

Summary and Conclusions

Information technology offers exciting opportunities, and its influence on the future of education is unavoidable. Ignoring this fact will leave educators left behind at the starting post. Instead, they must rise to the occasion and exploit I.T.'s possibilities to produce worthwhile and cutting edge learning tools. This thesis describes an intensive effort to develop such a tool, within the context of undergraduate structural engineering education.

The focus of this work was on achieving conceptual learning through computer-aided interactive tutorial experiences. Designed for elementary learning, the key to the effectiveness of the tutorials is deep feedback, combined with narrative threads and experiential opportunities. Within the context of structural engineering, the objective of these experiences is to instill in undergraduate students a qualitative and questioning nature, and sufficiently develop their understanding of structures so as to have them characterizing the behavior of a structure, instinctively.

Based on initial explorations into basic teaching methods and simulations, an initial

hypothesis of the methodology was developed. The next stage applied this methodology within the domain of structural engineering to establish a prototype module. This effort led to fine-tuning of the methodology, as well as allowing a valuable measure to be made, of its effectiveness at building the learning experiences for conceptual understanding.

The evaluation was a challenging process and the outcomes were mixed. The indicators for the methodology were positive, however. The most significant benefit of the evaluation effort was the experience gained from actually carrying the process out in a practical manner. The discipline of carrying out good evaluation in engineering education is still limited, so by making this effort, a valuable contribution was made for informing future assessment on similar projects.

Reaching the appropriate audience and testing the methodology through a one-time occurrence were the most challenging and influential aspects of the evaluation. With respect to the prototype module, its length and the complexity of its last quarter had a similarly dramatic impact on the evaluation results. The issues with the module do not reveal flaws in the methodology, but simply demonstrate points where the module was not successful in achieving the requirements of the methodology.

As regards the observations, the students' responses to the new teaching mode were very encouraging. The analysis of their interactions and test results demonstrated that the approach of engaging a student and drawing her through a problem was successful. Furthermore, through the evaluation efforts, the need for such a learning approach to teach conceptual material was demonstrated.

Thus, by actually creating and testing the learning experience, the research has demonstrated that the goals of conceptual learning and interactivity through common and transparent technologies can be achieved. Admittedly, the process of creating an effective learning experience is time consuming and laborious. The guidelines and techniques for doing this, however, are now established, ensuring a valuable and

practical contribution for future work to build on.

There are many exciting directions for future research. One of the more intellectually rigorous opportunities is in the development of adaptive education technologies. Realizing this research fully will require great technical skill, such as using intelligent agents and knowledge-based systems, however, the potential of adaptability to provide an intimate experience that fully caters to the student's needs and capabilities is very exciting. The methodology and findings provide a valuable basis for developing these adaptive experiences. The narrative, conversational format is ideal, so many of its aspects can be borrowed on with the adaptability aspects having the greatest effect on the environment's control path.

An alternative research direction, staying within the domain of common and easily accessible technologies, is the development of new means of engagement through these technologies. The simple multiple-choice problems have a surprising capability to them. Exploring and experimenting further with such problems so as to achieve reflective and challenging thinking and then systematizing the findings would be a valuable and extremely practical contribution to education technology.

Effectively integrating a module of libraries into a complete and enhanced environment, much like that discussed here and also in the author's Master's thesis [29] is another interesting challenge. Discovering the appropriate balance and cross-linking within the environment's architecture to cater for the students' differing ability and curiosity, yet still maintaining meaningful guidance and control paths, is an area of rich research.

The dilemma of the role of the analysis methods in engineering education, also needs to be resolved.

Additionally, future evaluation and assessment research, once carried out successfully will provide a rich source for examining student learning behavior, as well as allowing further refinement of the methodology and the development of more specific and

practical guidelines, i.e. how long is an "ideal" module? and how dependent is the length on the module's learning goals and complexity of topic?

Lastly, in order to encourage balanced and informed decision making for future education, it is salutary to recognize that focus must remain on the task and not the tool. A wonderful quote found in Norman's Book [25], "Things that make Us Smart",

"Science Finds,
Industry Applies,
Man Conforms.

Motto of the 1933 Chicago World's Fair

People Propose,
Science Studies,
Technology Conforms.

A much improved motto for the twenty-first century"

raises a very important issue. Emphasis must continue to be placed on maintaining the user's interest to enable learning through the best possible mode. Technology must be molded and compromised to humanity's needs and not vice versa. The direction computer development is taking indicates that this goal is becoming easier to accomplish. It is the responsibility of future research to capitalize on this.

Appendix A

Knowledge map for

undergraduate structural engineering

Undergraduate Structural Engineering

1 introduction
- nature of materials
- nature of environment
- structural components (methods of carrying loads)
- assemblies of these components
- structural responses

2 basic tools for determining structural behavior
- structural modeling and idealization
- static equilibrium
- constitutive relations
- compatibility of deformations
- linear vs. nonlinear systems (2nd order) *conceptual only*
- principle of superposition (linear
- statically determinate vs. indeterminate
- stability (also buckling)
- energy principles??

3 review of structural member
- cross-sectional properties of members
- behavior of members

4 beams/ one way slabs
- statically determinate
- statically indeterminate
- spring supports

5 frames
- plane
- multi-bay
- multi-story
- multi-bay, multi-story

6 planar grids (slabs)

7 dynamic loads and responses
- causes
- simple dynamic models
- design for effects

8 shells/plates

9 cables/nonlinear form dependent structures

Introduction:

```
                                                          ┌──────────────┐
                                                          │  strength    │
                                                          │  elasticity  │
                                            ┌──────────┐  │  ductility   │
                                            │definition│  │ σ_y, E, σ_u, ε│
                                            └──────────┘  │  σ_t vs. σ_c  │
                           ┌──────────┐                   └──────────────┘
                           │properties│                   ┌──────────────┐
                           └──────────┘                   │other important│
        ┌──────────────┐                                  │   material    │
        │nature of     │                                  └──────────────┘
        │materials     │                ┌─────────────┐   ┌──────────────┐
        └──────────────┘                │relationships│   │ Hooke's Law  │
                                        └─────────────┘   └──────────────┘
                        ┌─────────────┐  ┌─────────────┐  ┌──────────┐
                        │variation    │  │history/     │  │  why?    │
                        │between      │  │development  │  └──────────┘
                        │materials    │  └─────────────┘
                        │(examples)   │  ┌─────────────┐
                        └─────────────┘  │linear–ductile│
                                         │linear-brittle│
                                         └─────────────┘
                                         ┌─────────────┐
                                         │typical values│
                                         │for strains,  │
                                         │stress, limits,│
                                         │etc           │
                                         └─────────────┘
```

σ_y, E, σ_u, ε

σ_t vs. σ_c

- strength
- elasticity
- ductility
- other important material
- Hooke's Law

nature of materials → properties → definition / relationships

variation between materials (examples) → history/development → why?

linear – ductile / linear - brittle

typical values for strains, stress, limits, etc

```
                                                  ┌──────────────┐
                                                  │ dead load    │
                                    ┌──────────┐  │ live load    │
                                    │ causes of│  │ snow load    │
                                    │ loads    │  │earthquake load│
                                    └──────────┘  │ etc          │
                  ┌──────────┐                    └──────────────┘
                  │for strength│                  ┌──────────────┐
                  └──────────┘                    │point load/u.d.l.│
                                    ┌──────────┐  └──────────────┘
┌──────────────┐ ┌──────────┐      │ types of │  ┌──────────────┐
│nature of     │ │why care? │      │ loads    │  │gravity/lateral/│
│environment   │ └──────────┘      └──────────┘  │perpendicular  │
└──────────────┘                                 └──────────────┘
                                                 ┌──────────────┐
                                                 │dynamic/static │
                                                 └──────────────┘
                                    ┌──────────┐
                  ┌──────────────┐  │deflection│
                  │for serviceability│ control  │
                  └──────────────┘  └──────────┘
                                    ┌──────────┐
                                    │ motion   │
                                    │ control  │
                                    └──────────┘
                                    ┌──────────┐
                                    │durability│
                                    └──────────┘
```

nature of environment → why care? → for strength → causes of loads → dead load / live load / snow load / earthquake load / etc

types of loads → point load/u.d.l. / gravity/lateral/ perpendicular / dynamic/static

for serviceability → deflection control / motion control / durability

Diagram 1: structural components

- structural components
  - methods of carrying loads (+ components)
    - tension → stretch
    - compression
      - squash
      - instability/buckling
    - bending
      - stretch/squash
      - increased
      - instability/buckling
    - shear
    - tension
    - combination

    → how each works
    → dependence on loads
    → materials
    → history

  - support conditions/connections
    - effects
    - examples → pin/hinge roller/link fixed

Diagram 2

- assemblies of these → overview of structural
  - examples
  - demonstrate application of above components and supports

Diagram 3: structural responses

- structural responses
  - failure modes
    - strength
    - stability
      - overall
      - component buckling
  - (blank)
    - strength
    - stiffness
    - other
    → typical design criteria
      - *qualitative*
      - safety (strength/stiffness)
      - economy
      - architectural
      - services
  - analysis (structural) → qualitative overview only

Basic tools for determining structural behavior:

structural modeling and idealization

- symbology
- free body diagrams
- calc M, V, P, Δ, θ for simple structures

identification of basic "expected" behavior of simple structures (qualitative demo of conceptual understanding)

- determinate
- indeterminate

static equilibrium

- $\Sigma F_h = 0$
- $\Sigma F_v = 0$
- $\Sigma M = 0$
- sense of 2D/3D

statically determinant

constitutive relations

$f = P/A, \sigma = E\varepsilon$
$\varepsilon = \delta/L$
$\rightarrow \delta = PL/EA$
etc

compatibility of deformations

deformations of members must be compatible with connecting members and support conditions

indeterminant

linear vs. nonlinear systems (2nd order)
conceptual only

concepts

- when/why
- applications
- examples

- geometrically
- member level
- material

principle of superposition (linear systems)

- demo on beams
- comment about on frames but demo later
- works because eqns. of equilb. and constit. relations are linear

statically determinate vs. indeterminate

- degrees of redundancy
- degrees of freedom
- notion of continuity
- notion of relative stiffness

use of compatibility of deformations

```
                    ┌──────────────────┐        ┌──────────────────┐
                    │ stable structure │───────▶│ underdeterminate │
                    │   vs. mechanism  │        └──────────────────┘
┌──────────────┐    │ (i.e. overall    │        ┌──────────────────┐
│   stability  │───▶│    stability)    │───────▶│    load paths    │
│ (also        │    └──────────────────┘        └──────────────────┘
│   buckling)  │                                ┌──────────────────┐
└──────────────┘    ┌──────────────────┐    ┌──▶│      beams       │
                    │ geometric/member │    │   └──────────────────┘
                    │ stability and    │────┼──▶┌──────────────────┐
                    │    buckling      │    │   │      frames      │
                    └──────────────────┘    │   └──────────────────┘
                                            └──▶┌──────────────────┐
                                                │     3D forms     │
                                                └──────────────────┘
```

```
┌──────────────────┐    ┌──────────────────────┐
│ energy           │───▶│ is this necessary at │───────▶▶
│  principles??    │    │ undergrad. level??   │
└──────────────────┘    └──────────────────────┘
```

Review of structural member behavior:

effect on:

```
                                            ┌──────────────────┐
                                        ┌──▶│  indeterminate   │
┌──────────────┐   ┌──────────────────┐ │   └──────────────────┘   ┌──────────┐
│cross-sectional│  │ effect of area   │ │   ┌──────────────────┐┌─▶│  axial   │
│ properties of │─▶│ and moment of    │─┼──▶│  stresses/       │┤  └──────────┘
│   members     │  │ inertia to       │ │   │  deformation     │┤  ┌──────────┐
└──────────────┘   │ performance      │ │   └──────────────────┘└─▶│ traverse │
                   └──────────────────┘ │   ┌──────────────────┐   └──────────┘
                          │             └──▶│     buckling     │
                          ▼                 └──────────────────┘
                   ┌──────────────────┐
                   │ allows conceptual│
                   │ optimization of  │
                   │ member behavior  │
                   └──────────────────┘
```

```
                                    ┌──────────────────────┐
                                ┌──▶│ extension/ shortening │
                  ┌──────────┐  │   └──────────────────────┘  ┌──────────────┐
              ┌──▶│  axial   │──┼──▶┌──────────────────────┐─▶│ discussion and│
              │   │ loading  │  │   │       buckling       │  │ how to reduce │
              │   └──────────┘  │   └──────────────────────┘  │  it/restrain  │
              │                 │   ┌──────────────────────┐  └──────────────┘
┌──────────┐  │                 └──▶│ conceptual intro to  │
│ behavior │──┤                     │ P-Δ / 2ⁿᵈ order      │
│    of    │  │                     │ effects              │
│ members  │  │                     └──────────────────────┘
└──────────┘  │                     ┌──────────────────────┐
              │                 ┌──▶│ basic elastic bending│
              │   ┌──────────┐  │   └──────────────────────┘
              │   │ lateral  │  │   ┌──────────────────────┐
              └──▶│ loading  │──┼──▶│        shear         │
                  │transverse│  │   └──────────────────────┘
                  └──────────┘  │   ┌──────────────────────┐
                       │        ├──▶│        moment        │
                       │        │   └──────────────────────┘
                       │        │   ┌──────────────────────┐
                       │        ├──▶│ moment-curvature/    │
                       │        │   │ moment-area relations│
                       │        │   └──────────────────────┘
                       │        │   ┌──────────────────────┐
                       │        └──▶│       torsion        │
                       │            └──────────────────────┘
                       ▼
                    *beams*
```

Beams/one way slabs

```
statically
determinate
          → shear and BMDs
          → deformation and
            displacements
          → design of beams → static
                            → moving → influence lines

components
assemblies of
components/
systems

statically
indeterminate (fixed
end, multispan...)
          → superposition
          → design → static → uniform
                              → pattern
                    → moving
          → limit states → nonlinear/ductile
                           i.e. plastic hinges
          → support
            movements

spring supports → cable stayed
                  bridges
                → foundations
```

Frames

```
plane
├── statically determinate
│   ├── how work? ──┬── horizontal ──┬── axial, shear and BMDs
│   │               └── vertical      └── deflections rotations
│   └── ideal truss – special type of frame ──┬── arrangement of members – why no bending
│                                              └── location of loads
│
├── statically indeterminate (more conceptual)
│   ├── approximate methods ──┬── deformations and curvatures – inflection points
│   │                         ├── moment and shear diagrams
│   │                         ├── truss assumption, momentless frames
│   │                         └── validity of assumptions
│   ├── superposition ── simultaneous equations
│   └── support movement
│
├── different types (trusses too)
│   ├── frames ──┬── stability through bending ──┬── portal     for example:
│   │            │                               ├── gable       how do they behave?
│   │            │                               └── segmental
│   │            └── stability through axial ── braced through truss/axial action
│   └── trusses ── quick overview of types – how do they behave
│
└── ??arches - special type of frame
    ├── 4 hinged
    ├── 3 hinged
    ├── 2 hinged
    └──  ──┬── approximate methods of analysis
           └── superposition
```

multi-bay → one story rectangular building frames →
- approximate analysis
- exact analysis (superposition
- analysis for moving and live loads (patch loading too)
- design

multi-bay → bridges (example) →
- multispan rectangular bridges
- multispan arch bridges

multi-story →
- multistory building frames
- Vierendeel trusses

multi-bay, multi-story →

effects on behavior →
- of column stiffness
- of beam stiffness
- of alternative means of stability/stiffness →
  - bracing
  - shear walls

design of → parking structures to highrises →
- different issues (*i.e. movement joints*)
- case studies

nonlinear (ductile) behavior *links well with dynamics with ability to absorb energy, etc*

Dynamic loads and responses

```
causes  ──→  wind
        ──→  people/machinery  ──→  difference in
        ──→  earthquakes            their responses
```

```
simple dynamic  ──→  natural periods
models               – including simple
                     estimation for buildings
                ──→  damping
                ──→  free vibration
                ──→  forced vibration
```

```
design for  ──→  different responses need    ──→  i.e. stiffness needs for wind
effects          for different results/            vs. quakes,
                 design factors, etc               isolators, etc

            ──→  methods for fixing/         ──→  large scale conceptual
                 control devices                  i.e. stiffness/damping effects
                 i.e. isolators, dampers, etc     on multimodal structure
                                             ──→  single mode detail
                                             ──→  physical/picture examples
                                                  of devices
```

Appendix B

Screenshots of the prototype module

Figure B.1   **An early screen showing interface and setup of topic**

Figure B.2   Another early screen, before the "show me" icon is pressed

Figure B.3   After "show me" is pressed, with the "move on" icon displayed

To begin, we'll just stick with the single object, looking not only at how to make it stable but how to do it well! Later on in the module we'll look at the assemblies.

No matter what the buildings or bridges are that you'll be, or even are, designing, they will always have a *structural system* ▶ or backbone holding them up. It is this system that you must always check is stable.

True, it is often pretty obvious but you'd be surprised how frequently you still really have to look to ensure it is. Especially when we have a strongly *three-dimensional* structure.

Also, this is often the fun part. Once you get the hang of it, you can then work at stretching a structure's potential and make it a little more exciting (like this structure).

Figure B.4   After "follow on" is pressed and the next screen is available

For an unstable structure, loading typically causes massive deformations that often tend to increase as long as the load is applied. Unstable structures usually collapse completely and instantaneously as a load is applied.

A common form of such instability is in structures made up of an assembly of elements. Rigid body stability, as we'll be covering in this module, best describes these concerns.

The other types of instability are related to the behavior of specific scenarios with given dimensions, properties and loadings. For example, a column buckling or say a shallow roof snapping through. These types of instability are a lot more complicated and won't be discussed here.

Stability - what do we mean by this?

You probably already have a pretty good idea, right? It means something like.....
if an object or structure is stable then it won't move or deform too much or fall over when a load is applied.
Unlike this! ▶

This is basically all there is to it, however when designing structures there are different aspects of stability that need to be checked, or alternatively there are different types of *instabilities* to be considered.
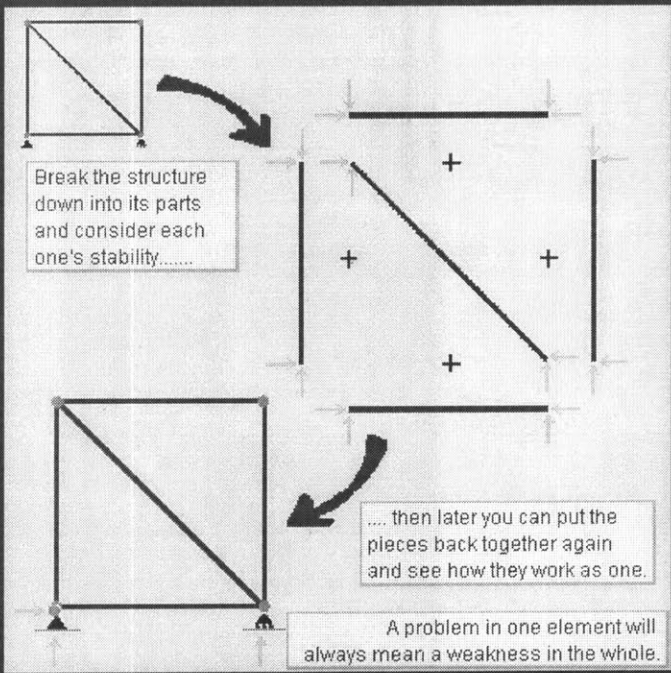
Figure B.5   Screen from figure B.1, with the pop-up box from the hyperlink displayed

You can only put restraints on where there are green dots.

To change a restraint condition of one of them, just drag a support from the menu at the bottom left. The arrows indicate which direction the beam will be restrained.

Once you think you've made the two-dimensional beam stable - test it out by applying a load.....
this time the load will just be a general 2D load that has both horizontal and vertical components.

drag some of these supports onto the body:

general load off

stability module

Figure B.6   The single beam exercise – the problem is posed

Well, that didn't work!

We need you to fix it, so have a look at the way in which it failed and see if you know what more it needs to be stable.

When you think you're ready press that "fix it" button and have a go! There is a hint on the next page if you need it - but try not to........

general load on

fix it

stability module

Figure B.7   The single beam exercise – a wrong solution and its animated feedback

Figure B.8   One of the follow-on problems from the beam exercise

Figure B.9   The feedback response to the first part of the problem with the second part posed
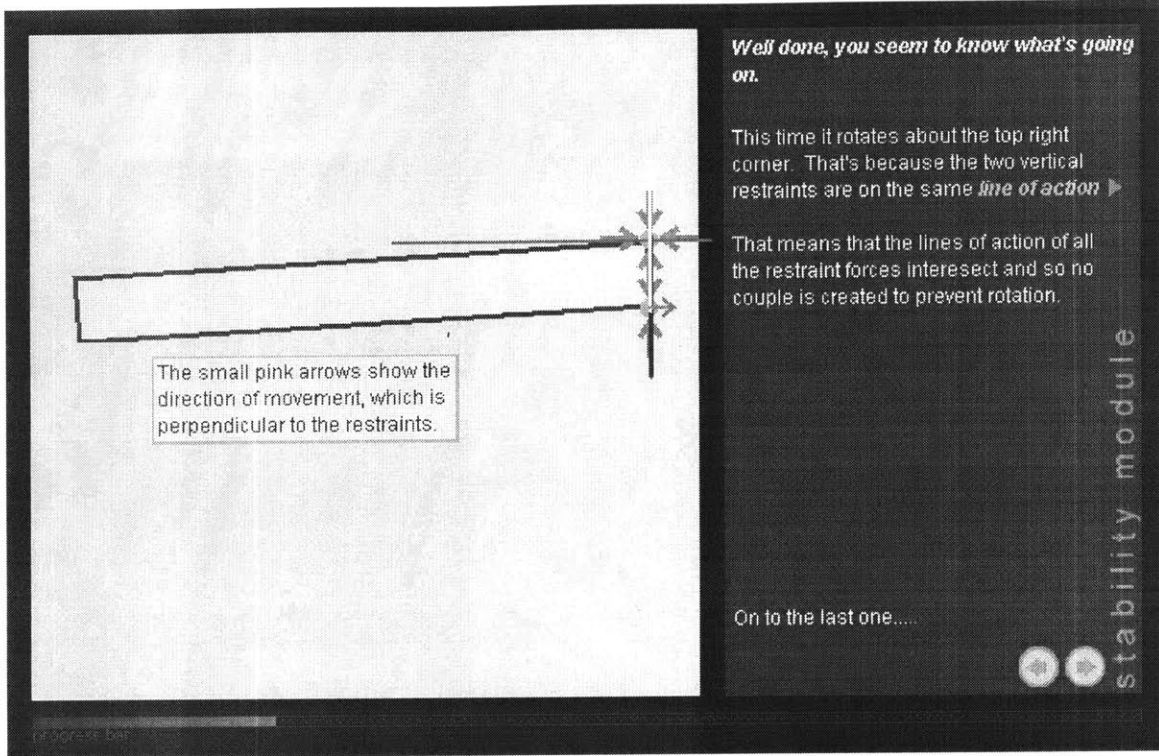
Figure B.10   The feedback response to the second part of the previous problem
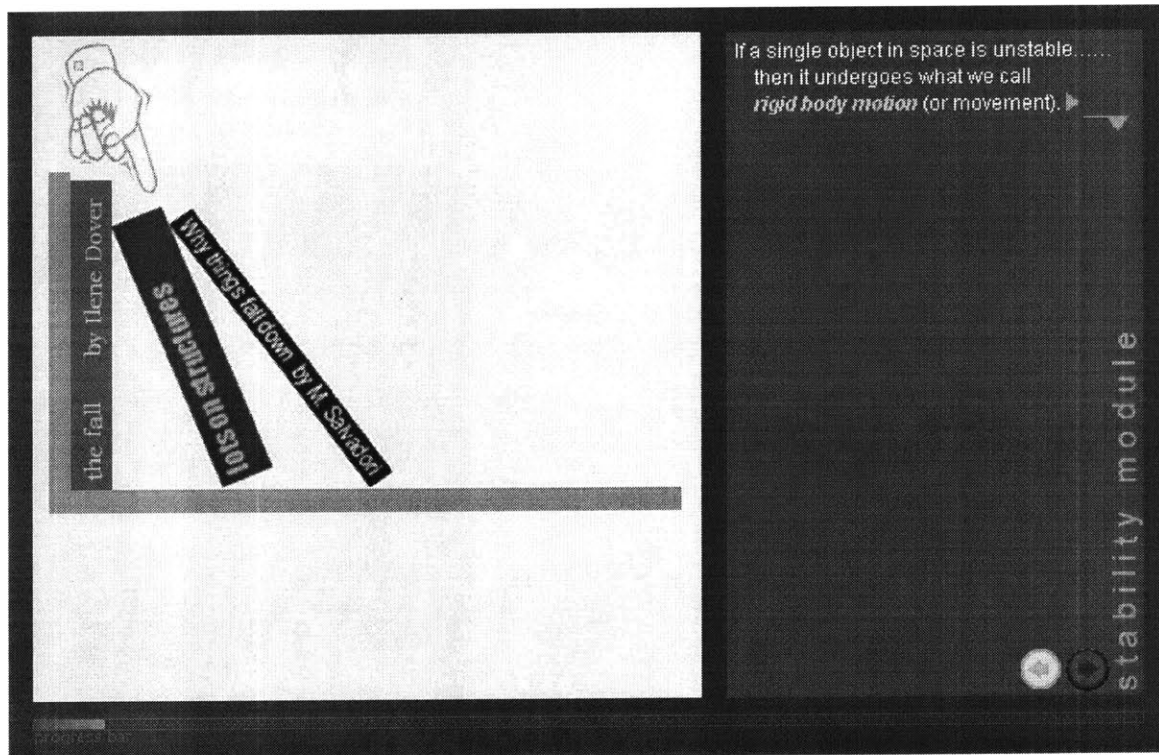
Figure B.11   The setup (part 1) for the rigid body motion(RBM) exercise
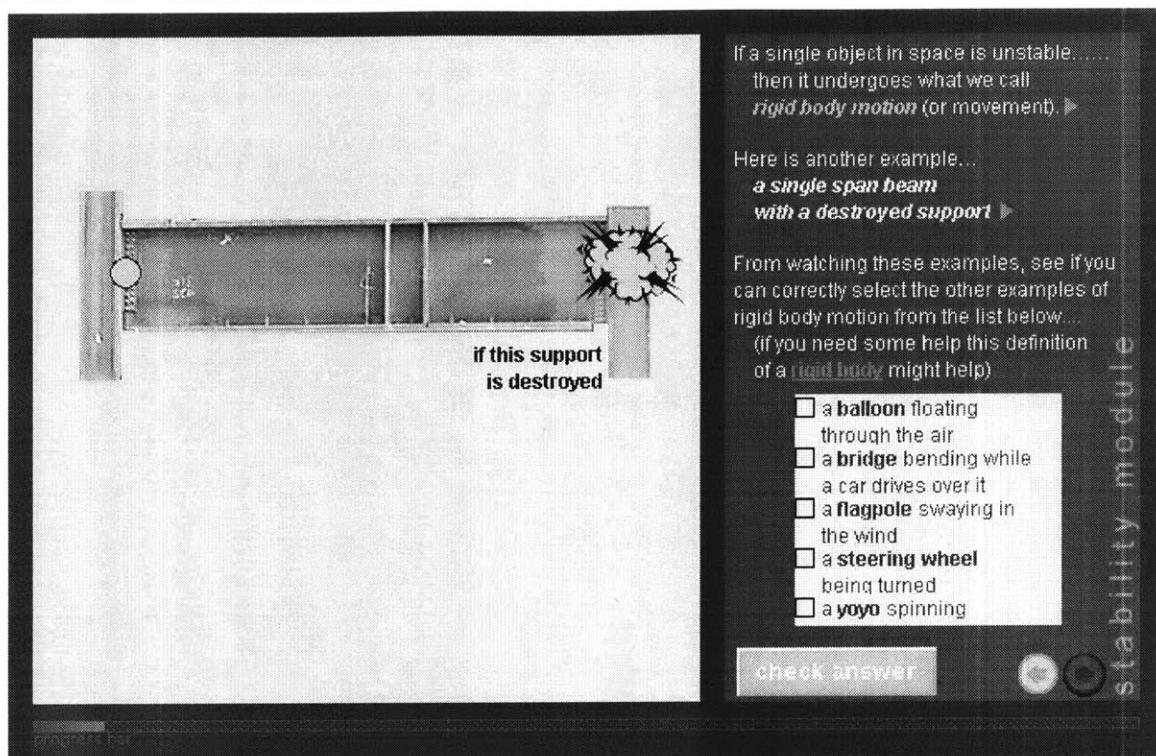
Figure B.12   The setup (part 2) and the posed problem for the RBM exercise
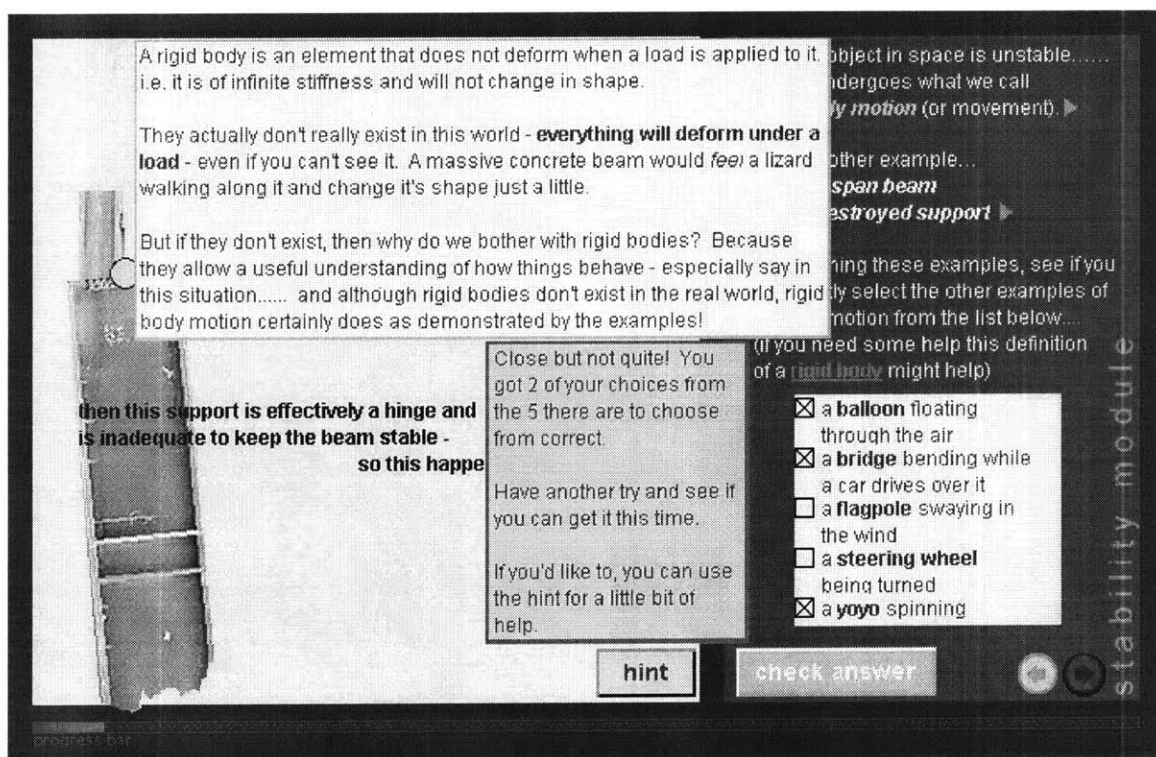
Figure B.13   The RBM exercise in progressing, displaying a response to an initial attempt and one of the available hints (the definition of a rigid body)
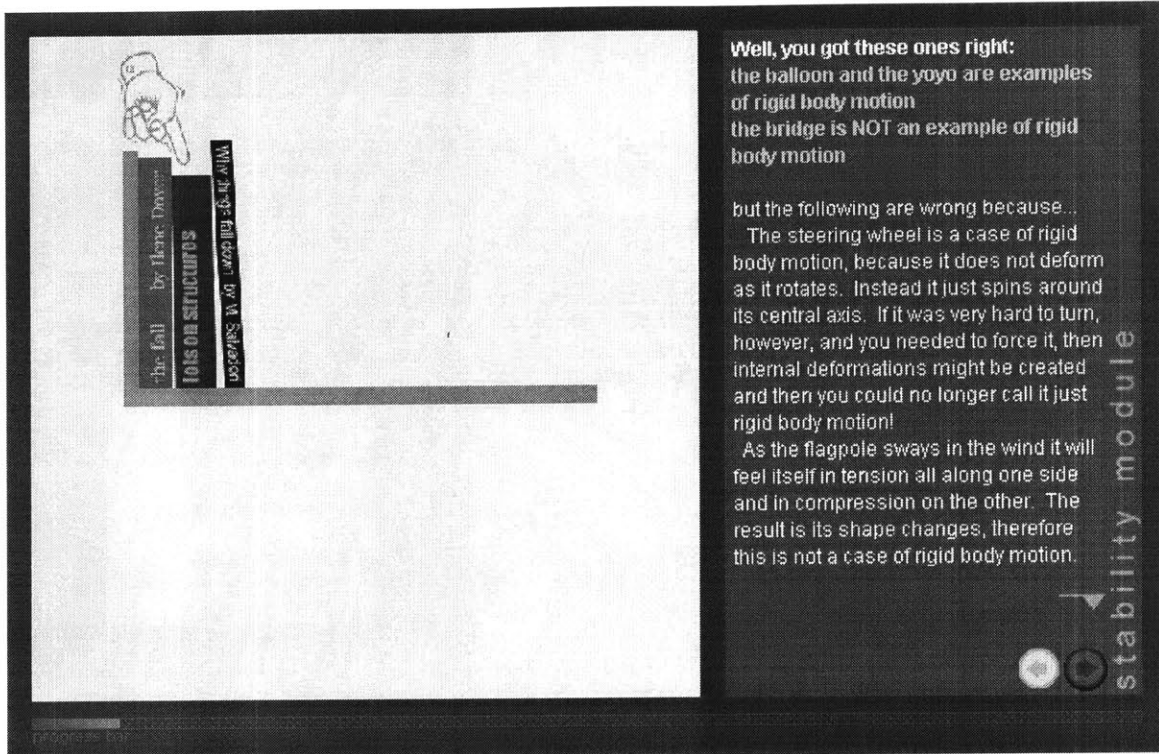
Figure B.14   The feedback for a final and incorrect attempt to the RBM exercise
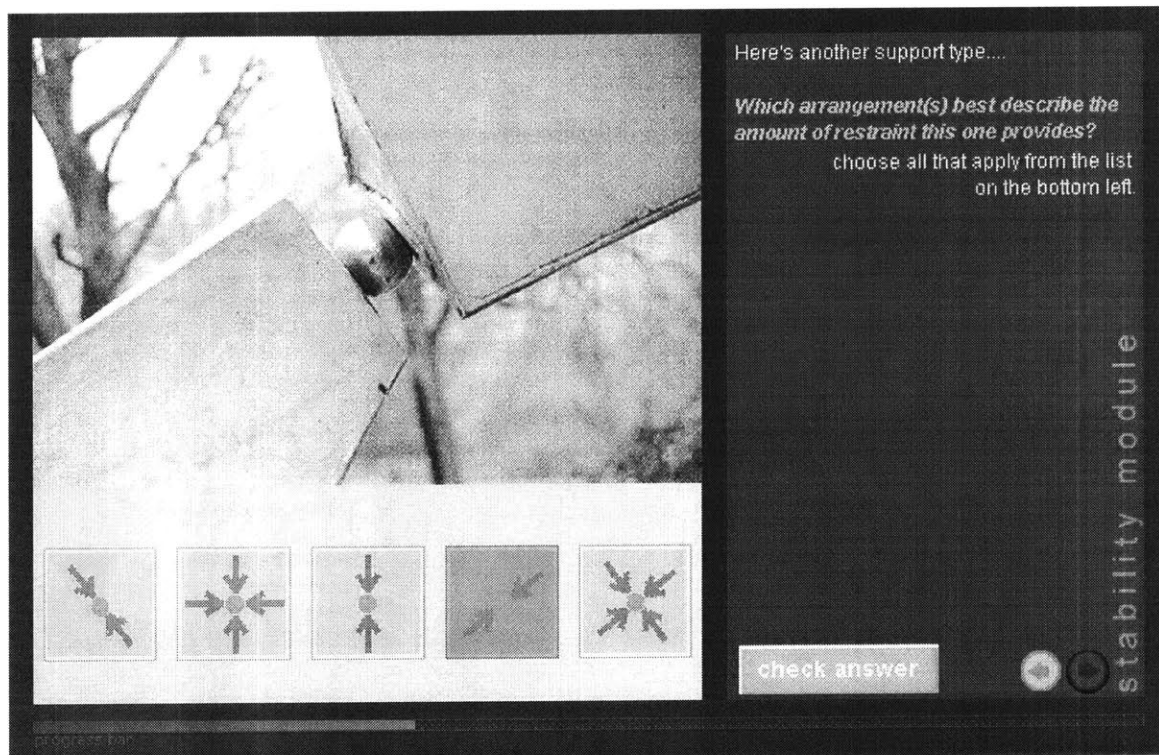
Figure B.15   The multiple-choice exercise for a "roller" support
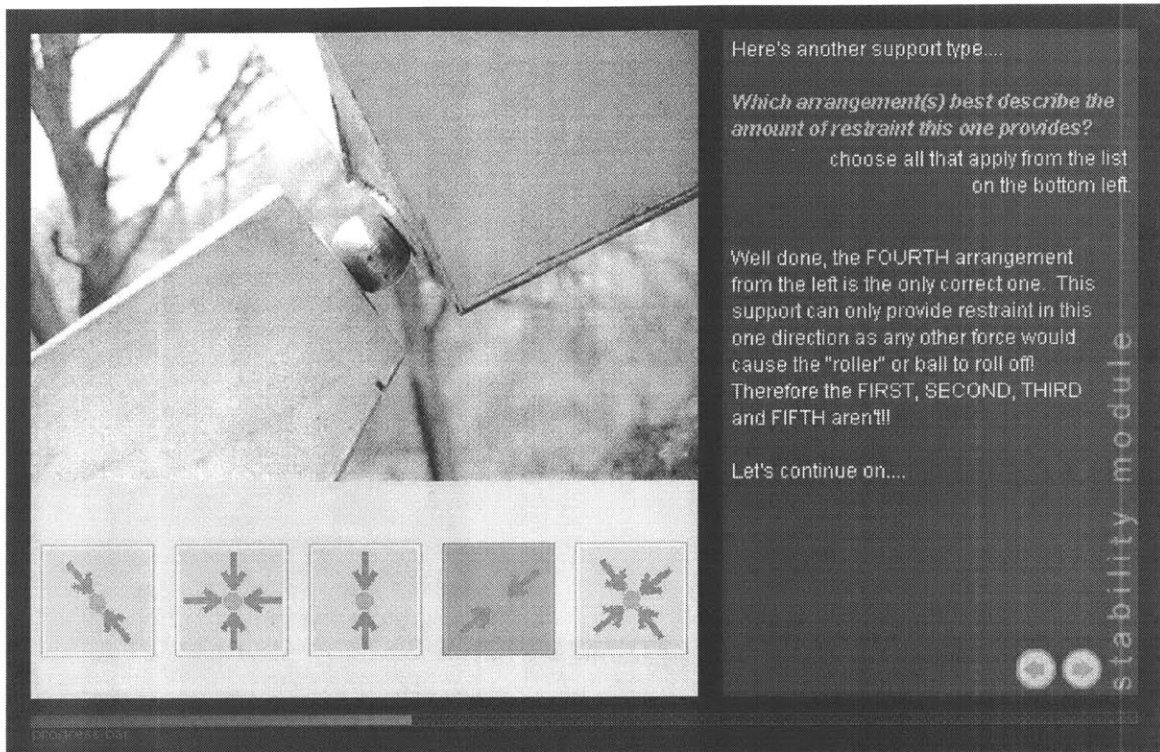
Figure B.16   The response to the correct choice for the "roller" exercise
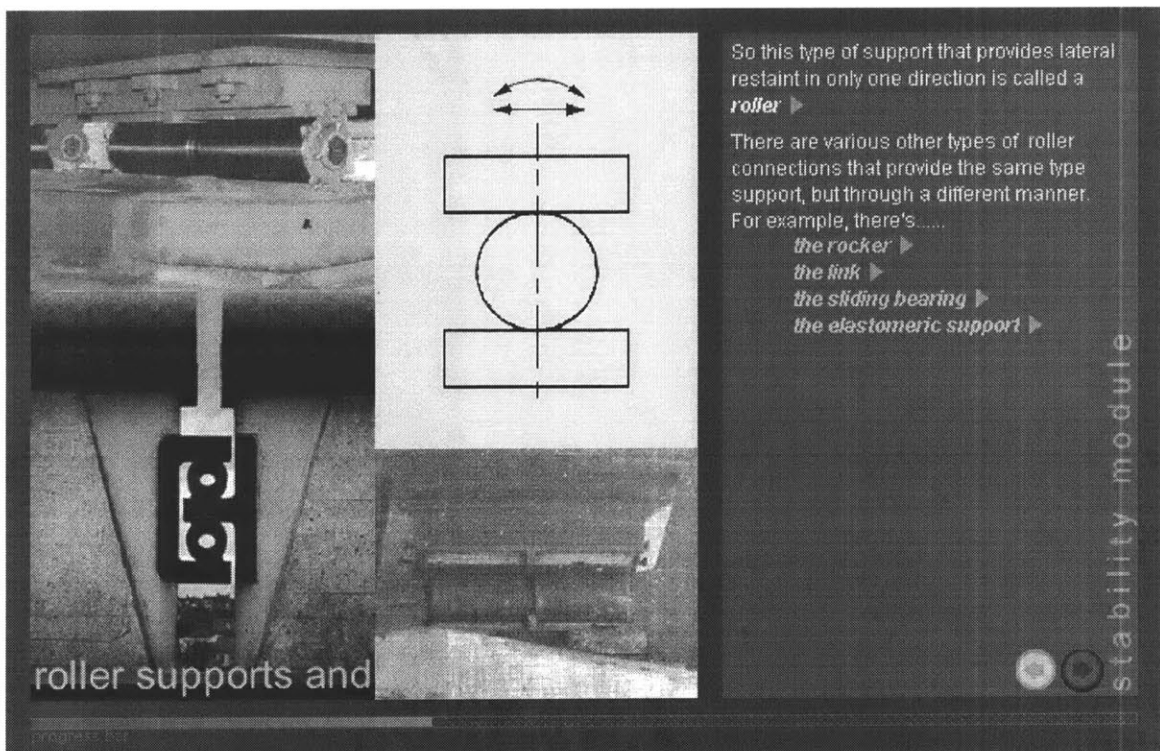
Figure B.17   The follow-on feedback introducing the concept of a "roller"
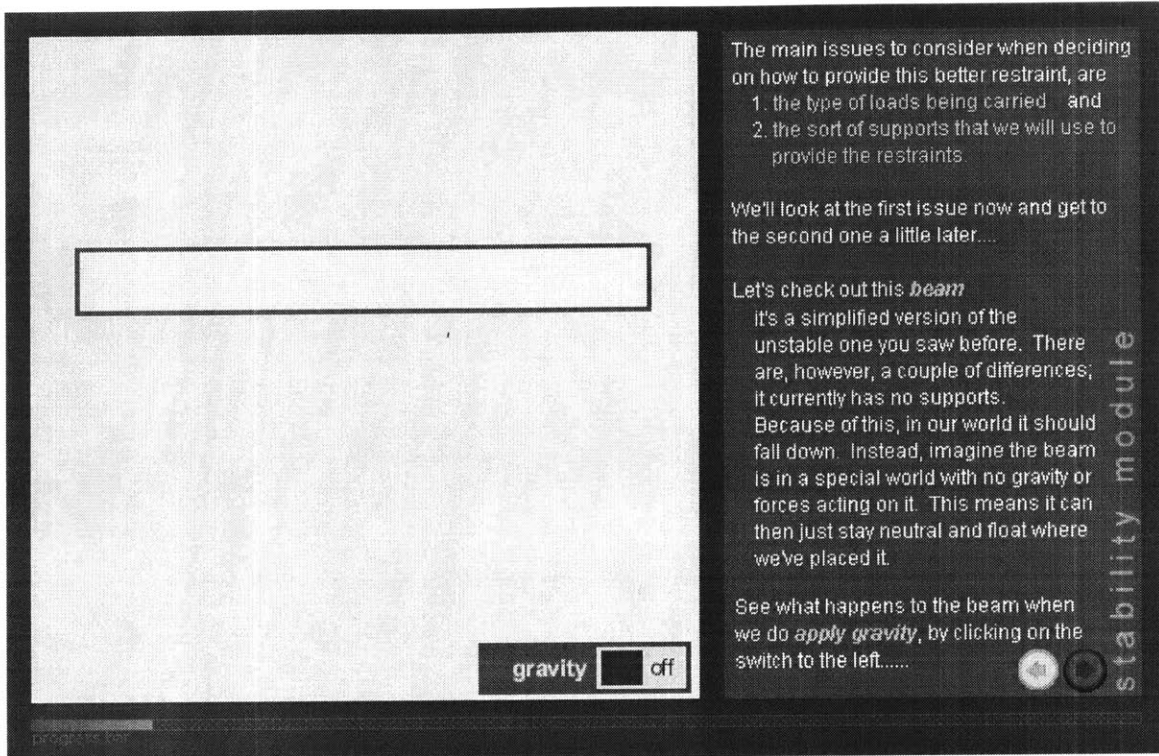
Figure B.18   The setup for the beam exercise of figures B.6 and B.7 – gravity off

Figure B.19   The setup for the beam exercise of figures B.6 and B.7 – gravity on

Figure B.20   The setup continued, applying a sideways nudge

Figure B.21   The setup continued with an optional discussion on where the horizontal forces can come from

To provide for a horizontal force we obviously need to include some sort of restraint to stop left and right motion.

By now you should be able to see that we need to consider forces from *any direction, regardless of magnitude* - *and always remember not to forget the third dimension.* We haven't really shown or discussed the third dimension much remember it is always there.

To make our beam stable, we could get really carried away and do something like *this* ▶

But that's kind of an overkill isn't it?!

So why don't we give you a go and see if you can come up with something better.

First let's reset the beam....

sideways nudge — on

gravity — on

Figure B.22   The end of the setup for the beam exercise – the extreme solution

rigid body stability

Welcome to the module on *Rigid Body Stability*. You'll soon be finding out more about the topic, but before you begin, here is a little about how to navigate through the module....

There are four main navigation methods - *try them out*:

▶   : show me

hyperlink : tell me more

▼   : move on

and the **forward** and **back buttons** shown below. As you can see, on this page only the forward button is currently active.

Your ID number for the evaluation is...   M743

It has been randomly generated.
Please note it down on your tests and survey.

Figure B.23   The introduction of the module – demonstrating the navigation tools

Figure B.24   The introduction continues, with the beam "show me" displayed

Figure B.25   The setup of the discovery path – divide and conquer

There, we're almost finished!
The concept of stability of a structure is obviously of great importance to structural engineering and architecture.

You can see, that the concept is *essentially the ensuring of an adequate path through the structure's elements, connections and out to the supports, for any load from any direction applied at any point.*

In this learning module, **we've explored this idea in detail for structures in two dimensions**. If we'd covered three dimensions as well, we'd be here forever.

You should always remember, however, that even though most of the examples you work with in class and here are two-dimensional, *we do live in a three-dimensional world and so stability must be considered in all three directions...*

stability module

Figure B.26   The conclusion – screen 1

Don't worry, the same rules apply. *You need to provide a lateral and a rotational restraint about all three axes.*

In doing this, there are two approaches; one is to consider the three-dimensional structure as a whole, and the other breaks the structure up into two perpendicular two-dimensional frames.

But that's all we'll mention on that for now, as you can imagine it is worth having its own module...

Please continue on to the last page for a small recap and one last *very important* step!

stability module

Figure B.27   The conclusion – screen 2

Appendix C

The tests and surveys used for evaluations

This appendix contains a copy of the instructions, survey and tests given to the students to evaluate the module and control.

C.1 Instructions provided with survey and tests

Thanks for taking the time out to do this evaluation of the "Rigid Body Stability". It should take you about and hour and a half to two hours total to complete the whole process. *There are four components* to it:

1. survey
2. test 1
3. the module itself
4. and finally, test 2

Please do them in the order they are listed here. The survey and test 1 are attached to this covering sheet. All instructions for completing them are included.

The module and an electronic copy of this evaluation package are available online at http://moment.mit.edu/modules/testing/toStartM1.htm. All instructions for using the module are provided with it.

All of the information being collected through **this evaluation is anonymous** and will only be used by the developers of the module for feedback and improvements. To achieve this you will be assigned an ID number that will be randomly generated when you begin the module, so *please be sure to mark this ID number done on all the survey and test pages.*

C.2 Survey for the "Rigid Body Stability" learning module

There are two sections to this survey; the first collects some background information on you to allow us to see how much experience and interest in Structures and Structural Engineering that you have. Please complete this section before beginning the module. The second section asks specific questions related to the module, its topic and your opinions of it. Therefore, it is obviously not supposed to be filled in until after you've finished the module. All of the collected information is anonymous and will only be used by the developers of the module for feedback and improvements, so **please be as candid as possible!**

id number: _____

You will be given this when you begin the module.
Please enter it on these survey pages and the test pages, when
required.

section 1   please complete before beginning the module

school and department enrolled in: _____

year enrolled in: (please circle which applies)   *freshman*   *sophomore*   *junior*   *senior*   *graduate*

your gender: *male*   *female*

structures course(s) you're currently enrolled in: _____

number of Structures/Structural Engineering classes you've taken before this semester: ___

how are your grades in these classes? (please circle which applies)   *not the best*   *reasonable*   *good*

do you find Structural Engineering interesting? why/why not? _____

are you planning on working as a Structural Engineer when you graduate? _____

do you have a favorite architect? If so who? _____

do you have a favorite engineer? If so who? _____

section 2   please don't complete until after finishing the module

approximate time it took for you to complete the module: _____ minutes

how would you rate your knowledge to the topic of *Rigid Body Stability* prior to doing this module?

   poor   -   -   *reasonable*   -   -   *excellent*

please select the point on the quality scale that best describes your general opinion on the following aspects of the module. Feel free to add comments or give specific examples as desired.....

length: *too long*   -   -   *just right*   -   -   *too short*

comment? _____

pace: *too slow*   -   -   *just right*   -   -   *too fast*

comment? _____

difficulty/challenge: *too easy*   -   -   *just right*   -   -   *too difficult*

comment? _____

interest value of the topic: *not at all*   -   -   *mildly*   -   -   *very*

comment? _____

relevance of the topic: *not very*   -   -   *mildly*   -   -   *very*

comment? _____

relevance of subtopics: *none were*   -   -   *some were*   -   -   *all were*

were there any particular subtopics that you would have liked to see more or less expansion on?

_____

other comments? _____

interface design: (please make a selection for each subcategory)

layout: *confusing*   -   -   -   -   -   *very clear*

navigation: *too easy*   -   -   *just right*   -   -   *too difficult*

font size: *too small*   -   -   *just right*   -   -   *too large*

other comments? _____

help provided for problems: (please make a selection for each category)

amount: *didn't use*   *not enough*   -   -   *sufficient*   -   -   *too much*

usefulness: *didn't use*   *no useful*   -   -   *useful*   -   -   *gave away too much*

other comments? _____

text – in general: (please make a selection for each category)

tone: *too familiar*   -   -   *just right*   -   -   *too formal*

amount: *too brief*   -   -   *just right*   - -   *too longwinded*

clarity: *too vague*   -   -   *just right*   -   -   *too obvious*

content detail: *not specific enough*   -   -   *just right-*   -   -   *too detailed*

other comments? _____

animations: *poor*   -   -   -   -   -   *excellent*

comment? _____

any other comments or problems/bugs you spotted? _____

_____

_____

_____

_____

C.3 Tests for evaluating the module and control

C.3.1 Test A

Please answer the questions to the best of your ability. You will see that this test is quite similar to the first one you did. Remember if you do not know the answer do the best you can, let us know and move on, but please do try! All of the collected information is anonymous and will only be used for feedback and future improvements of this module and ones like it.

id number: _____

1. What are the equations of equilibrium for a *two*-dimensional rigid body?

2. Indicate whether each of the following bodies is stable for any type of load.
   i)   if it is stable, is the body determinate or indeterminate?
   ii) if it is unstable, please mark on the body how you'd change the supports slightly so as to make it determinate.

a)

b)

stable	*or*	*unstable ?*
if stable then		
determinate	*or*	*indeterminate ?*

stable	*or*	*unstable ?*
if stable then		
determinate	*or*	*indeterminate ?*

c)

d)

stable	*or*	*unstable ?*
if stable then		
determinate	*or*	*indeterminate ?*

stable	*or*	*unstable ?*
if stable then		
determinate	*or*	*indeterminate ?*

3. Indicate whether each of the following structures is stable for any type of horizontal or vertical load.

   i) if it is stable, how many degrees of redundancy do the structures have (determinate = 0)?

   ii) if it is unstable, please mark on the structure how you'd change the supports slightly so as to make it determinate.
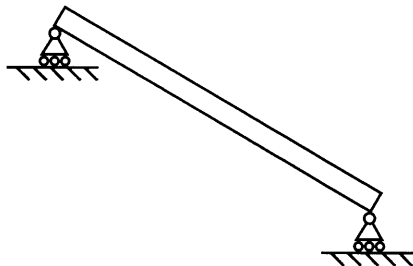
a)

b)

the elements crossing each other are not connected

stable   or   unstable ?
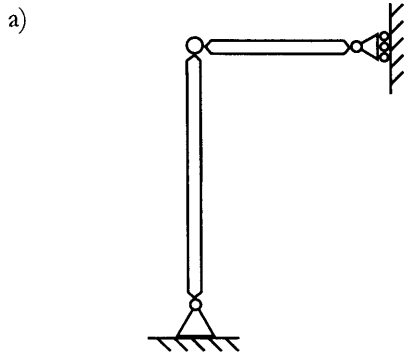*if stable then*
  determinate,   1 degree of redundancy,
  2 degrees of red.   or 3 degrees of redundancy?

stable   or   unstable ?
if stable then
  determinate,   1 degree of redundancy,
  2 degrees of red.   or 3 degrees of redundancy?

c)

the elements crossing each other are not connected

d)

stable   or   unstable ?
if stable then
  determinate,   1 degree of redundancy,
  2 degrees of red.   or 3 degrees of redundancy?

stable   or   unstable ?
if stable then
  determinate,   1 degree of redundancy,
  2 degrees of red.   or 3 degrees of redundancy?

4. Determine the reactions for the following bodies. Please show all your working and diagrams. If you run out space, use the backside of these sheets.

a)

M

L

b)

c)

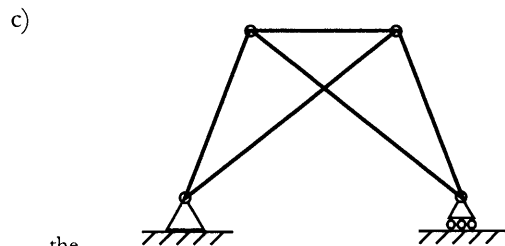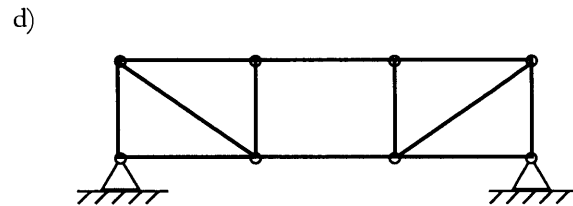5. Which way would this structure deflect due to the applied load, P? Up, down, to the left, to the right or a combination of these? Please give a brief explanation why. Assume the members are not rigid; i.e. they're elastic.

6. Consider each element in the following structures. Due to the applied loads, P, indicate whether you think their internal force is in tension, compression, zero or you don't know.

a)

b)
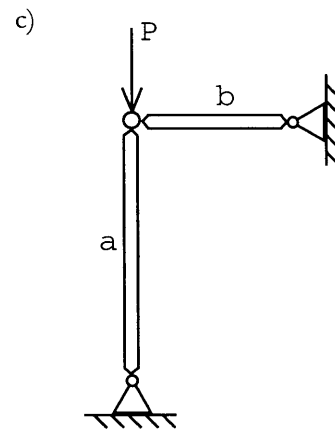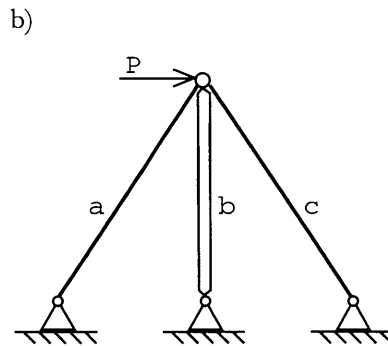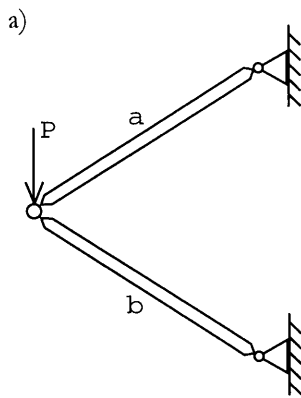
elements a and c are cables.

c)

member a?	member b?	member a?	member b?	member a?	member b?
tension	*tension*	*tension*	*tension*	*tension*	*tension*
compression	*compression*	*compression*	*compression*	*compression*	*compression*
zero	*zero*	*zero*	*zero*	*zero*	*zero*
don't know	*don't know*	*don't know*	*don't know*	*don't know*	*don't know*

member c?
tension
compression
zero
don't know

C.3.2 Test B

Please answer the questions to the best of your ability. If you do not know the answer do the best you can, let us know and move on. It is important however that you try as the results of this test and the rest of the testing package are of great interest to the developers of the module. All of the collected information is anonymous and will only be used for feedback and future improvements of this module and ones like it.

id number: _____

1. What are the equations of equilibrium for a *two*-dimensional rigid body?

2. Indicate whether each of the following bodies is stable for any type of load.
    i)   if it is stable, is the body determinate or indeterminate?
    ii) if it is unstable, please mark on the body how you'd change the supports slightly so as to make it determinate.

a)
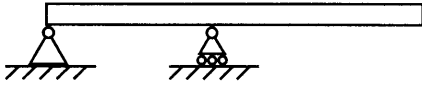
stable   or   unstable ?
if stable then
  determinate   or   indeterminate ?

b)
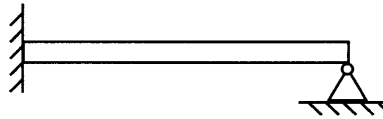
stable   or   unstable ?
if stable then
  determinate   or   indeterminate ?

c)

stable   or   unstable ?
if stable then
  determinate   or   indeterminate ?

d)

stable   or   unstable ?
if stable then
  determinate   or   indeterminate ?

3. Indicate whether each of the following structures is stable for any type of horizontal or vertical load.

    i)   if it is stable, how many degrees of redundancy do the structures have (determinate = 0)?

    ii)   if it is unstable, please mark on the structure how you'd change the supports slightly so as to make it determinate.

a)

b)

stable   *or*   *unstable ?*
if stable then
   determinate,   *1 degree of redundancy,*
   2 degrees of red.   *or* *3 degrees of redundancy?*

stable   *or*   *unstable ?*
if stable then
   determinate,   *1 degree of redundancy,*
   2 degrees of red.   *or* *3 degrees of redundancy?*

c)

d)

the
elements crossing each other are not connected

stable   *or*   *unstable ?*
if stable then
   determinate,   *1 degree of redundancy,*
   2 degrees of red.   *or* *3 degrees of redundancy?*

stable   *or*   *unstable ?*
if stable then
   determinate,   *1 degree of redundancy,*
   2 degrees of red.   *or* *3 degrees of redundancy?*

4. Determine the reactions for the following bodies. Please show all your working and diagrams. If you run out space, use the backside of these sheets.

i)

P

L

ii)

iii)

5. Which way would this structure deflect due to the applied load, P? Up, down, to the left, to the right or a combination of these? Please give a brief explanation why. Assume the members are not rigid; i.e. they're elastic.
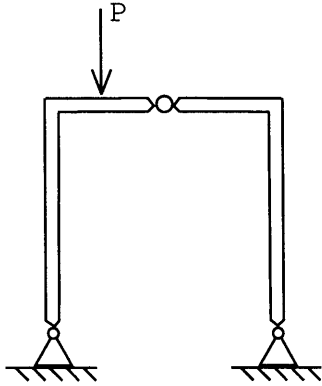
7. Consider the following structure, which consists of a heavy rigid plate supported by four columns. Assume that all the connections are pins/hinges and that the structure can be subjected to horizontal loads acting at any point on the rigid plate and in any direction.
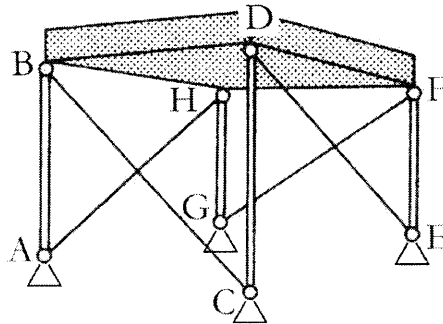
a) If the diagonal members BC, DE, FG, and HA are rigid members capable of carrying either tension or compression, is the assembly a stable configuration of elements? Why?

b) If the diagonal members are all cable (tension only) elements is the assembly stable? Why?

c) If case (b) is not stable, can additional cable elements be added to make the assembly stable? If so, where? Draw them on the figure above.

Appendix D

The Evaluation Results

Unless noted otherwise, the legend for all the graphs is in the bottom right hand corner of each page.
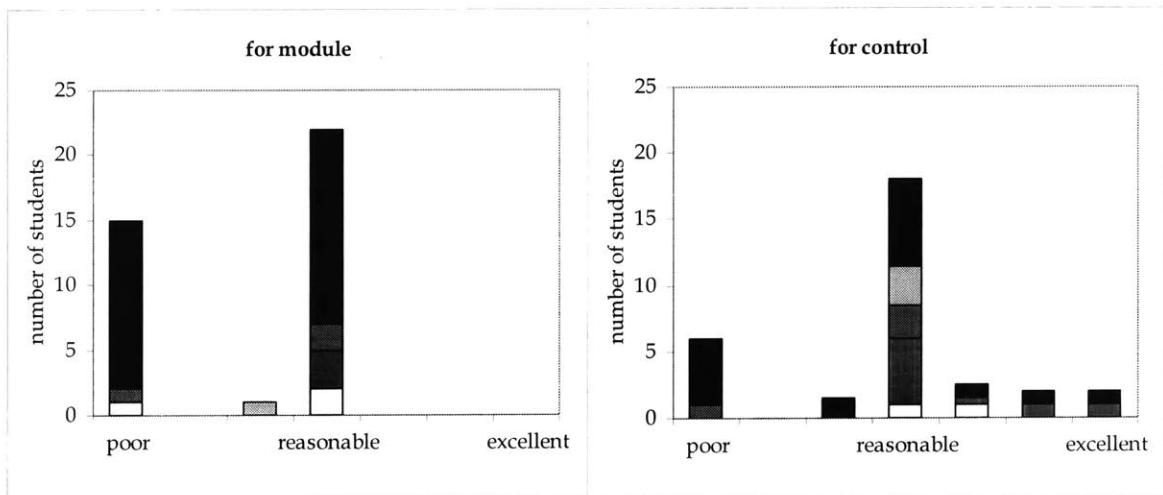
D.1 Results for the survey

Figure D.1.1   Responses on prior knowledge

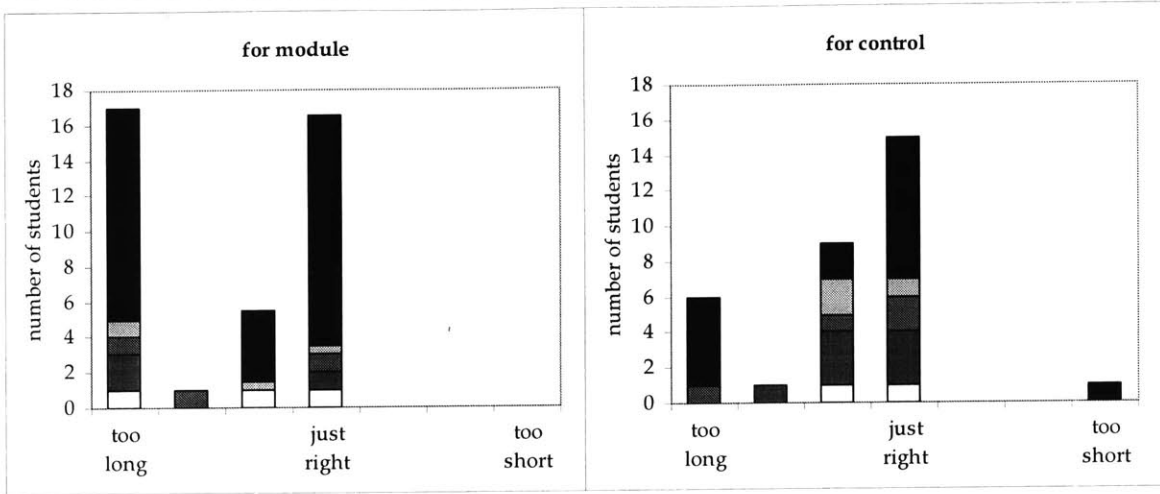□ MIT eng. ■ NEU ■ MIT arch. ▨ Harvard ■ Wentworth

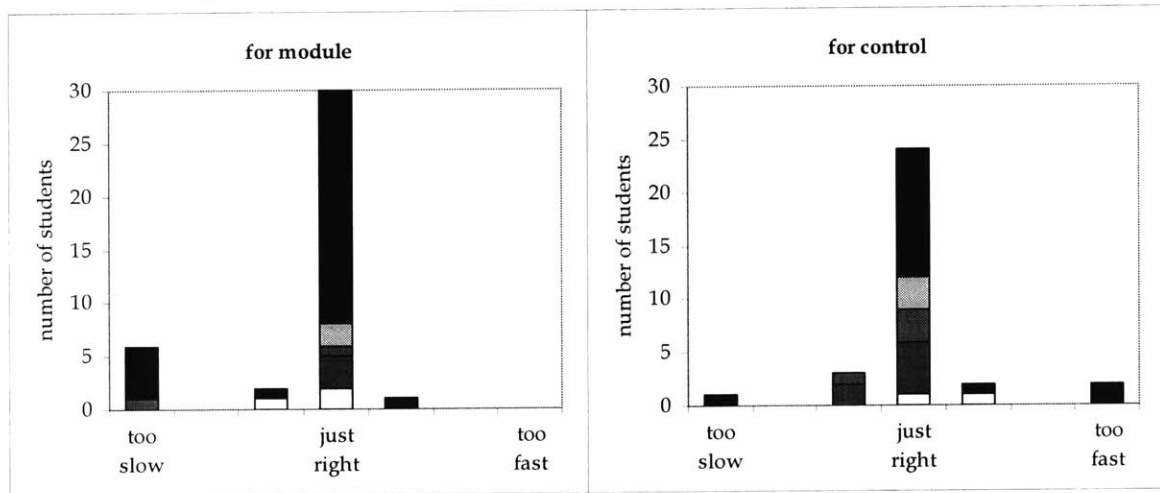**Figure D.1.2   Responses on the length of the module/control**

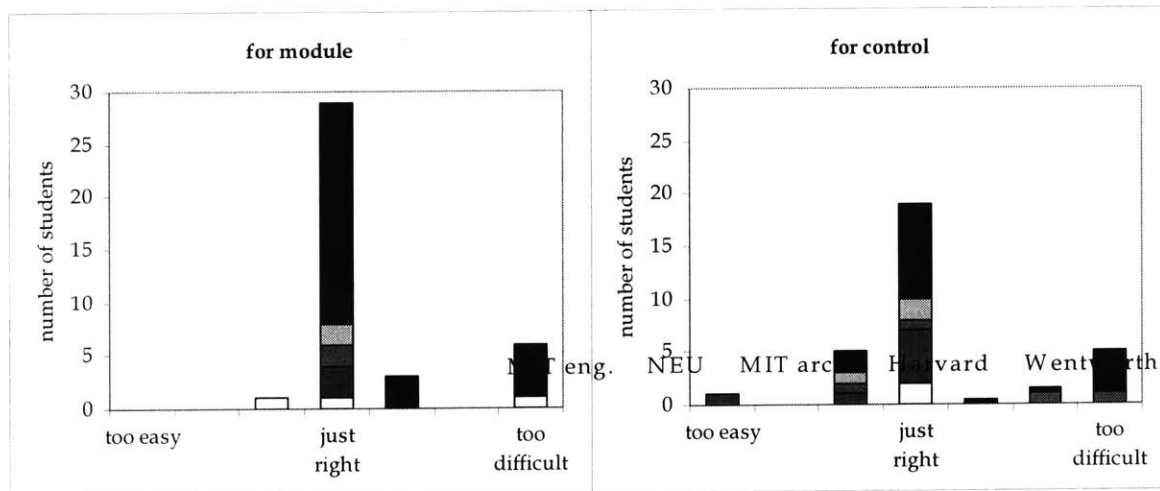**Figure D.1.3   Responses on the pace of the module/control**

Figure D.1.4   Responses on the level of difficulty of the module/control

☐ MIT eng.   ■ NEU   ▨ MIT arch.   ▨ Harvard   ■ Wentworth
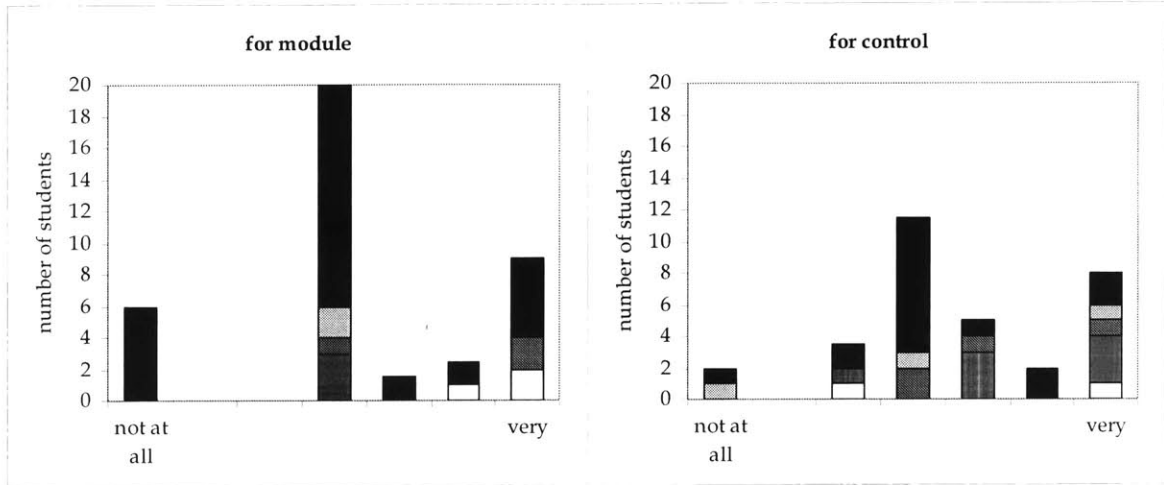
Figure D.1.5   Responses on the level of interest of the module/control
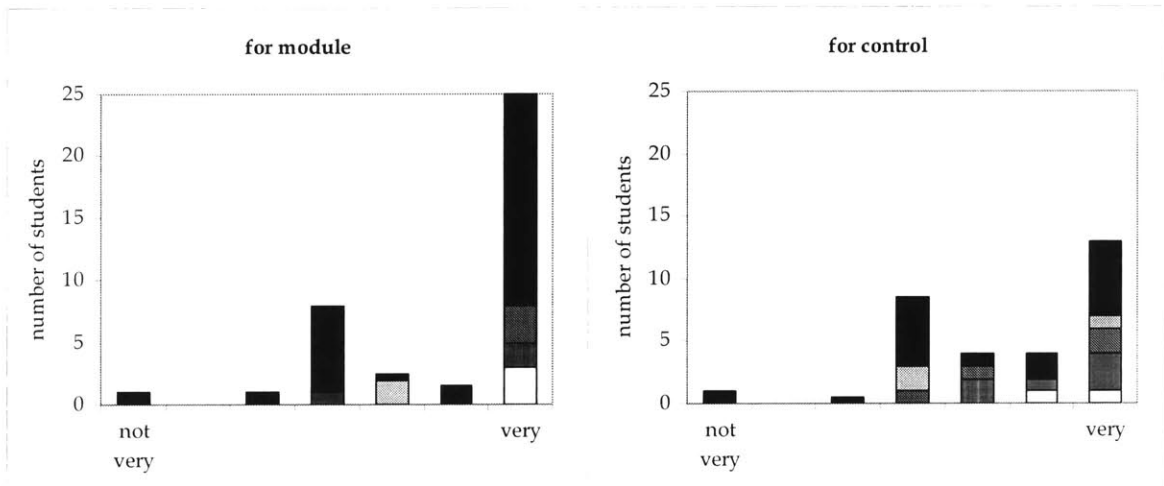

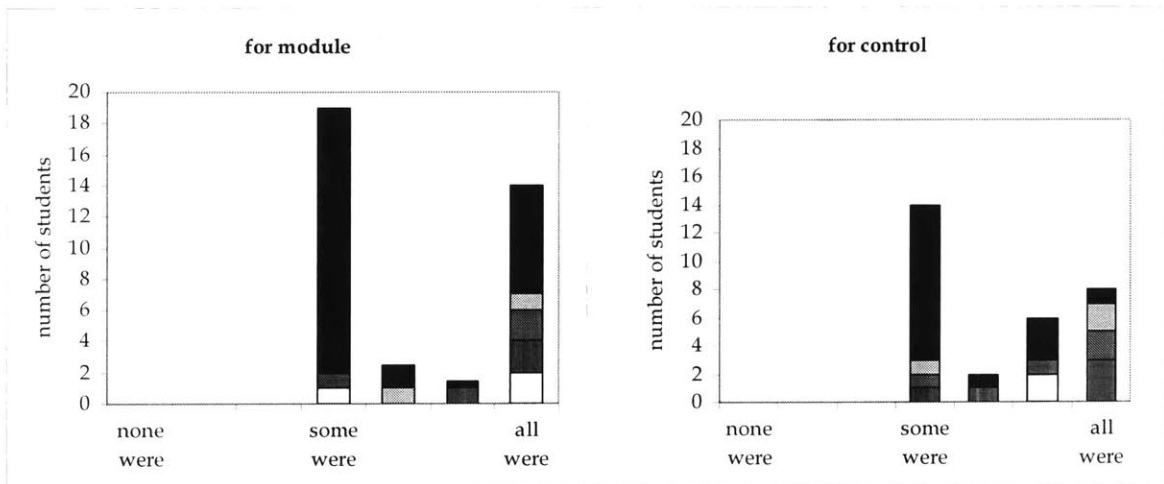Figure D.1.6   Responses on the relevance of the topic of the module/control

Figure D.1.7   Responses on the relevance of the subtopics of the module/control

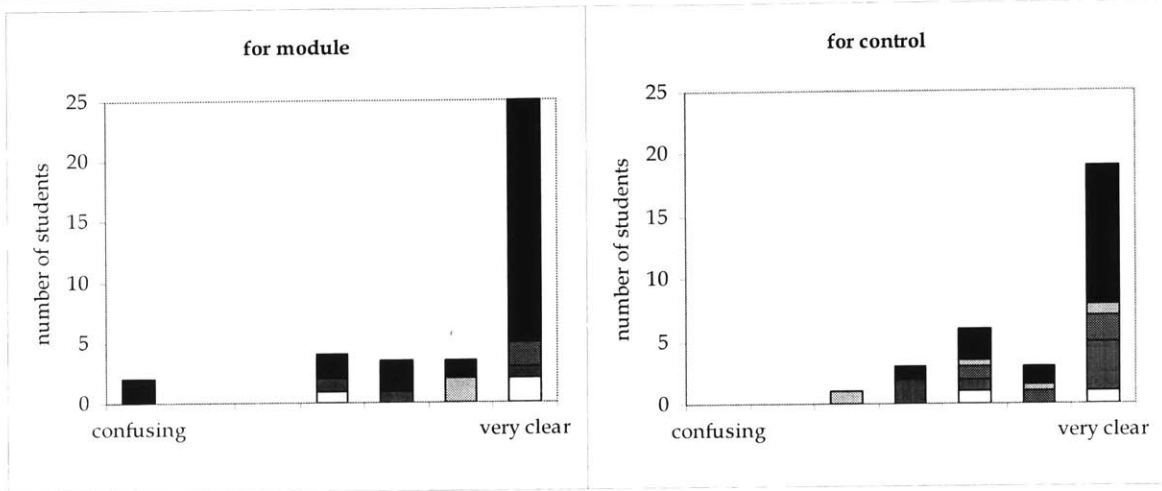□MIT eng. ■NEU ■MIT arch. ▨Harvard ■Wentworth

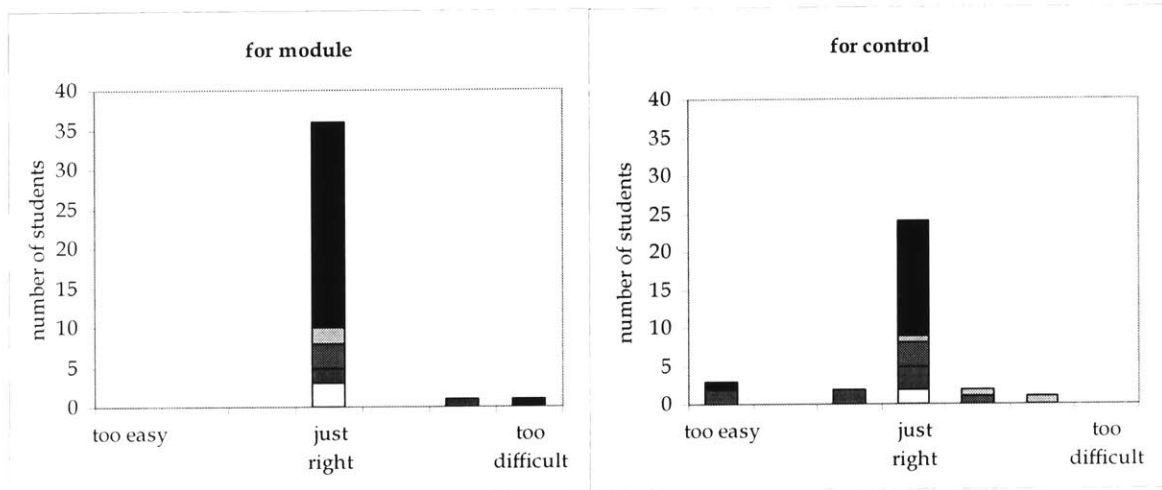**Figure D.1.8   Responses on the layout of the interface of the module/control**

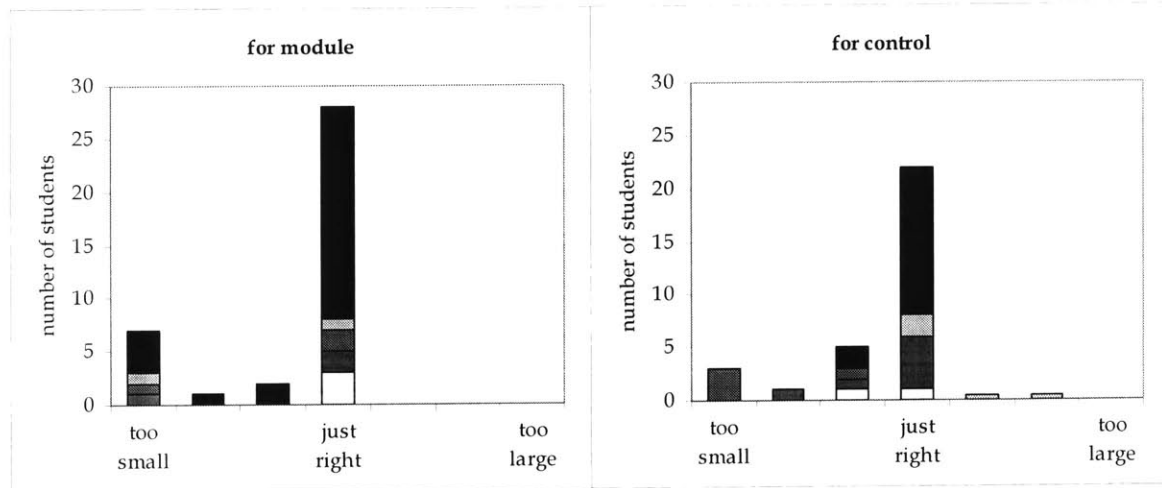**Figure D.1.9   Responses on the navigation tools of the module/control**

Figure D.1.10 Responses on the font size of the module/control

□MIT eng. ■NEU ▩MIT arch. ▤Harvard ■Wentworth

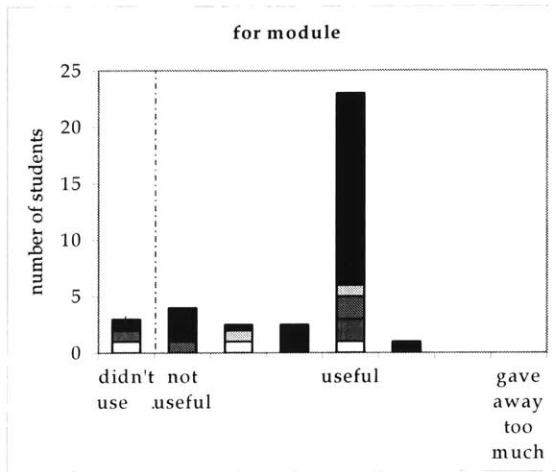**for module**

Figure D.1.11 Responses on the amount of help the module provides *(n/a for control)*

for module
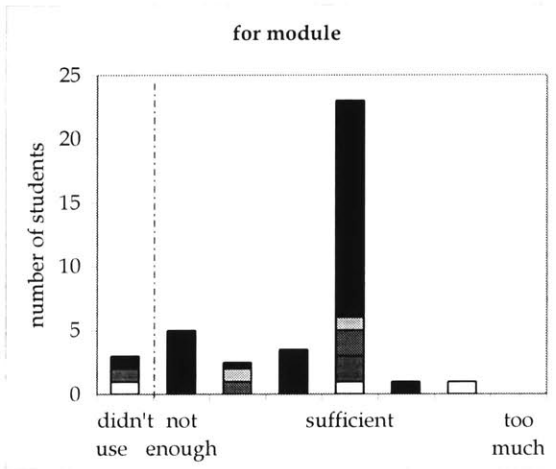
Figure D.1.12 Responses on usefulness of help the module provides *(n/a for control)*

for module   **for control**

Figure D.1.13 Responses on the tone of the text in the module/control

□ MIT eng. ■ NEU ■ MIT arch. □ Harvard ■ Wentworth

Figure D.1.14 Responses on the amount of text in the module/control

Figure D.1.15 Responses on the clarity of the text in the module/control
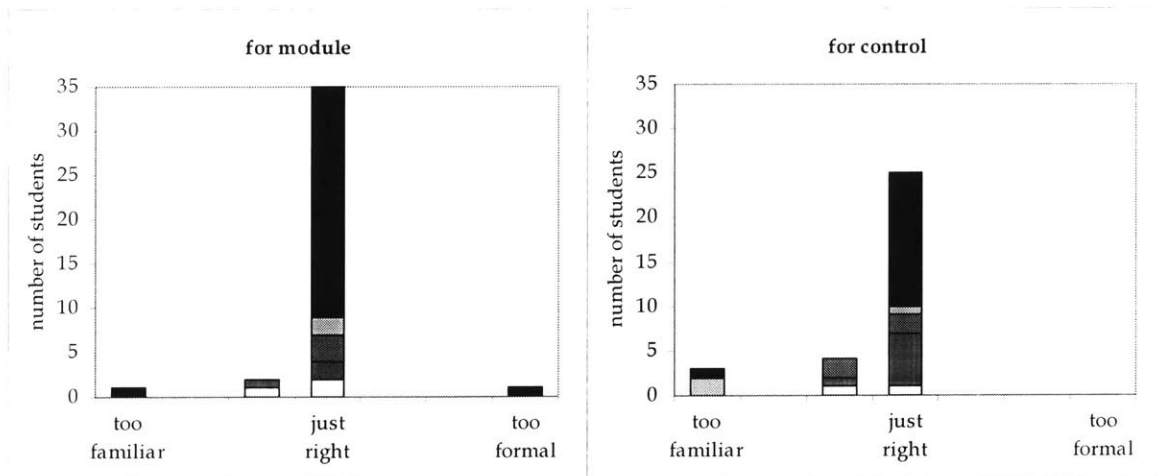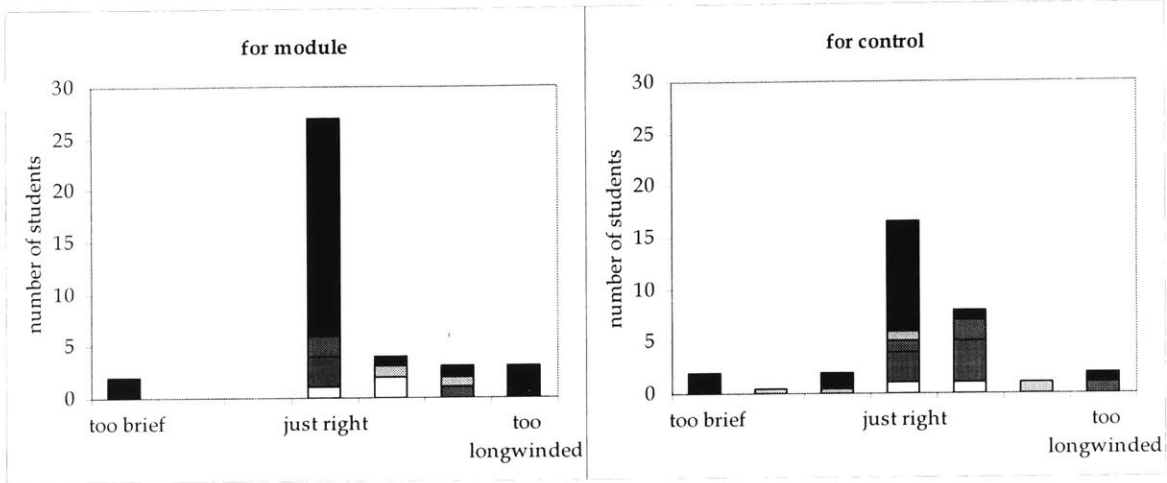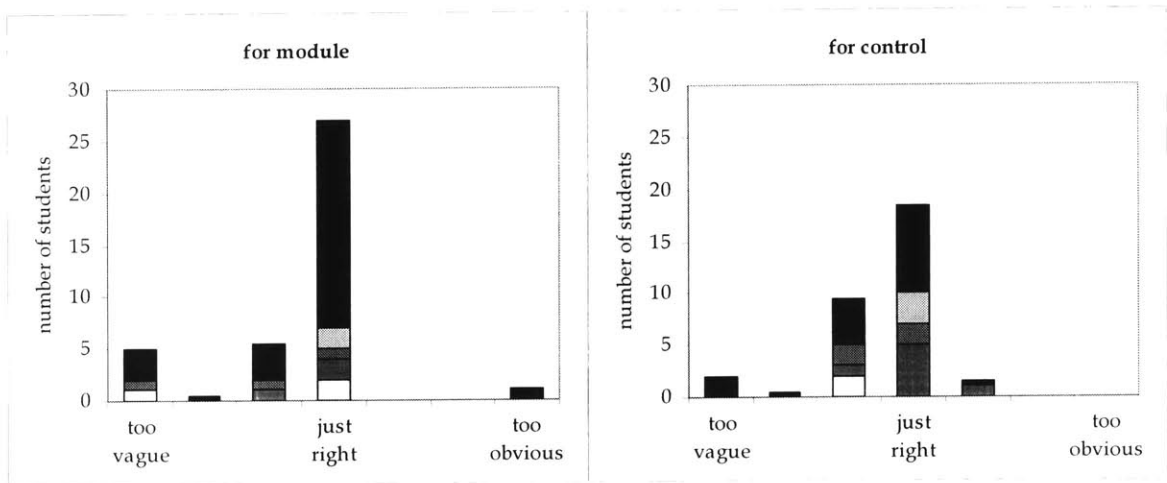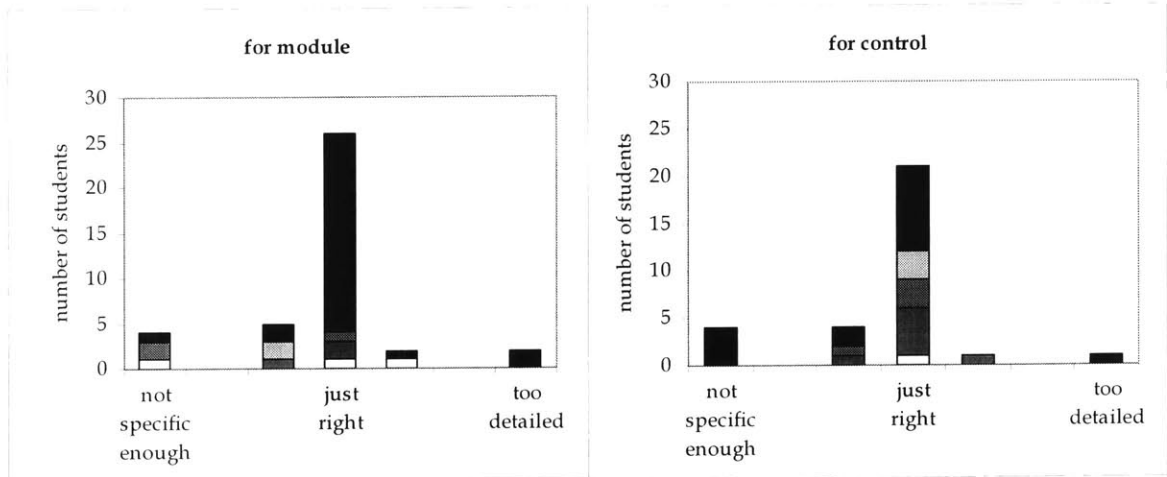

Figure D.1.16 Responses on the level of content detail in the module/control

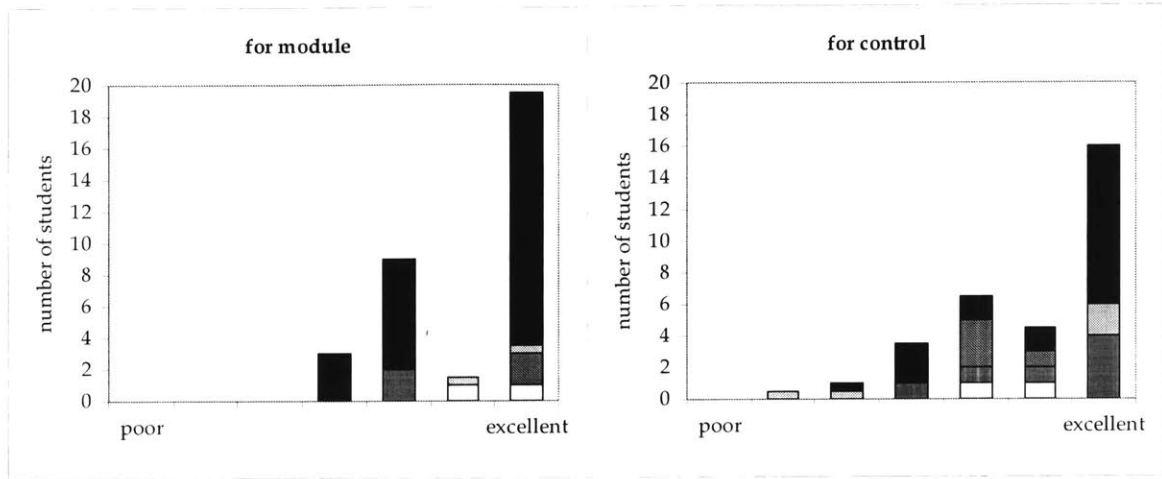□ MIT eng. ■ NEU ▨ MIT arch. ▨ Harvard ■ Wentworth

Figure D.1.17 Responses on the quality of the animations in the module/control

□ MIT eng. ■ NEU ■ MIT arch. ▨ Harvard ■ Wentworth

Table D.1.1 A summary of the student profiles – part 1

	id	year	gender	no. of prev. classes	grades	like eng.?	work as engineer	favorite architect	favorite engineer
MIT (eng.)	M361	sophomore	male	0	good	yes	perhaps	no	no
	M660	sophomore	female	0	reasonable	yes	yes		
	M633	sophomore	female	0	reasonable	yes	no	yes	yes
	B641	sophomore	female	0	good	yes	yes	n/a	n/a
	B950	sophomore	male	0	reasonable	yes	not sure	no	no
NEU	M142	junior	male	2	good	yes	hmm...		
	M251	junior	male	2	good	yes	undecided	yes	yes
	M304	middle junior			good	yes	yes		
	M538	sophomore	male	about 5	reasonable	yes	no	no	no
	M674	junior	male	3	reasonable	no	no	no	no
	B227	junior	female	2	reasonable	yes	no	no	no
	B522	junior	male	2	reasonable	yes	not sure	no	no
	B567	junior	male	2	good	yes	possibly		
	B573	junior	male	2	reasonable	somewhat	no	no	no
	B634	mid junior		2	reasonable	yes	no	no	no
	B645	junior	male	2	reasonable	no	no	no	no
	B912	junior	female	3	good	yes	no	no	yes
MIT (arch.)	M470	graduate	male	2	good	yes	yes	yes	yes
	M756	graduate	male	1	good	yes	maybe	yes	yes
	MXX	graduate	male	2	not the best	yes	no	yes	yes
	B425	graduate	female	1	good	yes	no	yes	
	B505	graduate	female	2	good	yes	no	yes	
	B510	graduate	male	1	good	yes	no		yes
	B610	graduate	male	1	good	yes	no	yes	yes
Harvard	M402	graduate	female	1	not the best	yes	no	no	no
	M713	graduate	male	0	reasonable	somewhat	no	yes	no
	B444	graduate	male	1	reasonable	yes	no	yes	yes
	B461	graduate	male	0		no	yes	no	yes
	B593	graduate	female	1	good	somewhat	no	yes	yes

Table D.1.2   A summary of the student profiles – part 2

	id	year	gender	no. of prev. classes	grades	like eng.?	work as engineer	favorite architect	favorite engineer
	M136	sophomore	female	0	good	yes	not sure	no	no
	M153	freshman	male	0	reasonable	yes	no	no	no
	M193	sophomore	female	1	good	yes	no	yes	
	M231	sophomore	male	0	reasonable	yes	no	yes	no
	M305	sophomore	male	1	reasonable	yes	unsure	yes	no
	M332	sophomore	female	0	not the best	yes	no	no	no
	M357	sophomore	male	0	good	yes	no	yes	no
	M374	sophomore	female	0	good	yes	no	no	no
	M380	sophomore	male	0	reasonable	no	no	yes	no
	M389	sophomore	male	0	not the best	no	no	no	no
	M408	sophomore	male	0	good	yes	maybe		no
	M419	sophomore	female	0	reasonable	yes	no	yes	n
	M429	sophomore	female	0	reasonable	yes	no	yes	
	M440	sophomore	male	2	good	yes	probably not	yes	no
	M464	sophomore	male	0	reasonable	yes	no	yes	no
	M496	sophomore	female	0		no	No	yes	no
	M514	junior	male	1	not the best	yes	no	yes	
	M526	sophomore	male	0	reasonable	yes	unsure	yes	yes
	M580	sophomore	male	0	reasonable	not so far	no	no	no
	M581	sophomore	male	0	not the best		no	yes	no
	M643	sophomore	female	0	not the best		no	yes	
	M646	sophomore	male	0	good	no	no	yes	no
	M653	sophomore	male	0	good	yes	possibly	no	no
	M663	sophomore	male	0	reasonable	yes	no		
	M678	sophomore	female	0	not the best	yes	no	no	no
	M715	sophomore	female	0		yes	no	no	no
	M747	sophomore	male	0		yes	may be	no	no
	M768	sophomore	male	0	reasonable	yes	no		yes
	M823	sophomore	male	2	reasonable	somewhat	probably not	yes	no
	M948	soph./junior	female	3	not the best	somewhat	no	yes	no

(Left margin label, rotated: Wentworth)

Table D.1.3 A summary of the student profiles – part 3

|	id	year	gender	no. of prev. classes	grades	like eng.?	work as engineer	favorite architect	favorite engineer
	B213	sophomore	male	0	good	yes	no		
	B245	sophomore	female	1	not the best	yes	possibly		
	B347	sophomore	male	2	reasonable	yes	no	n/a	n/a
	B352	sophomore	female	0	reasonable	yes	no	yes	no
	B415	sophomore	female	0	good	yes	no	no	no
	B416	junior	male	1	good	yes	no	yes	
	B486	sophomore	female	0	reasonable	yes	no	yes	
Wentworth	B489	sophomore	male	0	reasonable	yes	no	no	no
	B490	sophomore	male	0	not the best	somewhat	no	yes	no
	B505	sophomore	male	0	good	yes	no	no	no
	B513	sophomore	female	0	reasonable	somewhat	no	yes	no
	B580	sophomore	male	0	reasonable	somewhat	no		
	B678	sophomore	male	0		no	no	no	no
	B761	sophomore	male	0	reasonable	yes	no		
	B800	sophomore	male	0	good	yes	no		
	B881	junior	male	1	reasonable		possibly		no
	B926	sophomore	female	2	reasn. to good	yes	no	no	no

D.2 Results for the tests
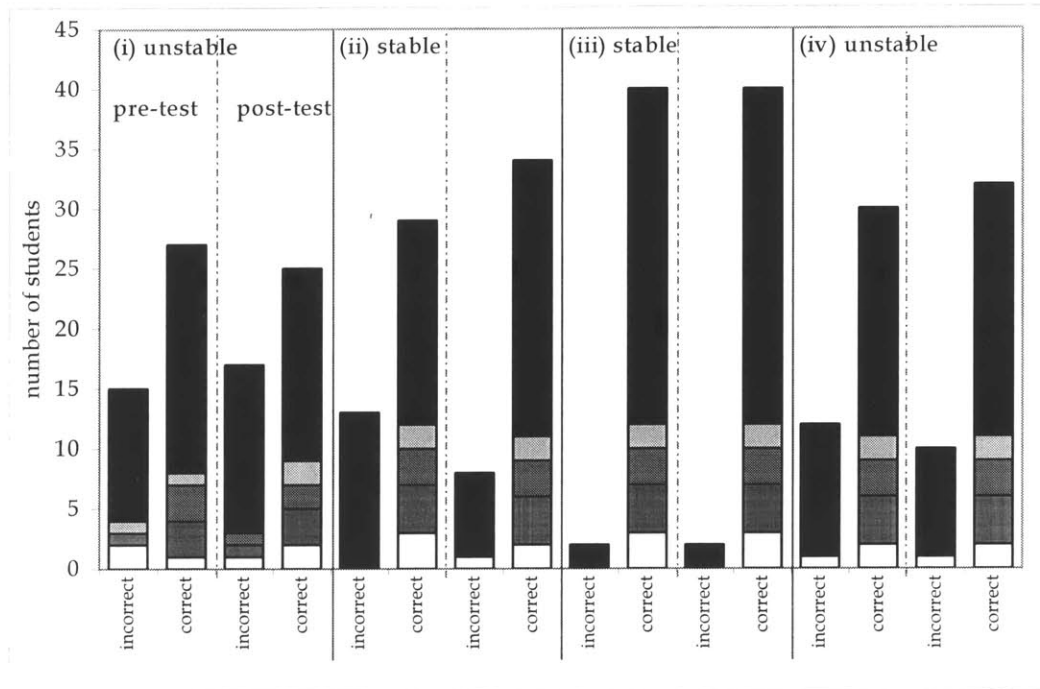
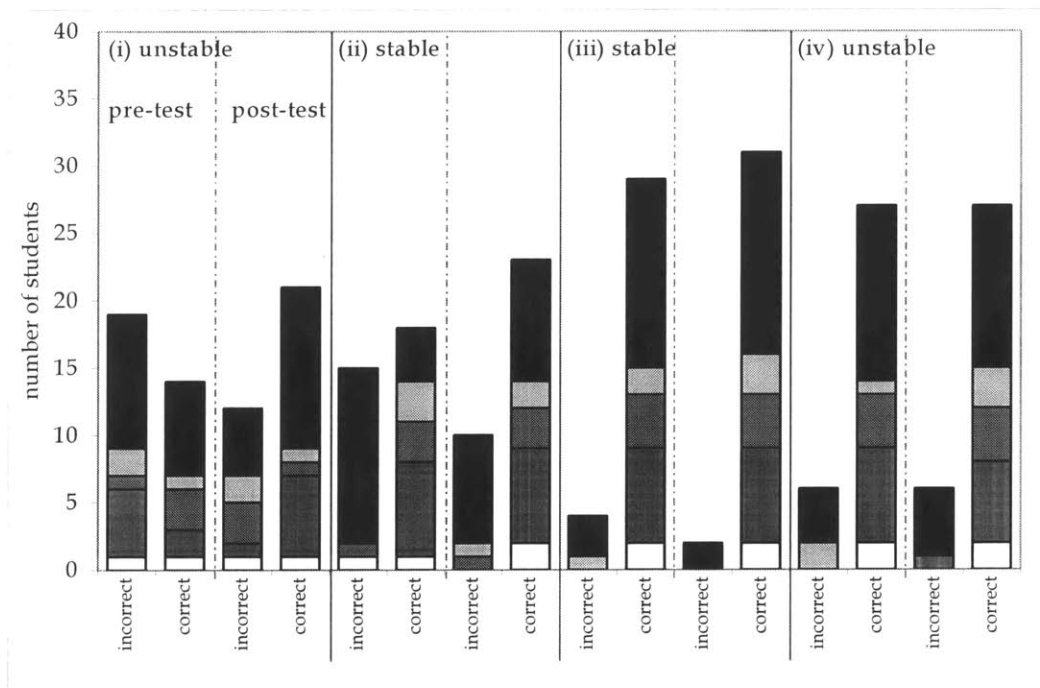**Figure D.2.1** Q2(a) is the body stable? Grade breakdown for each body for *module*

Figure D.2.2 Q2(a) is the body stable? Grade breakdown for each body for *control*

□MIT eng. ■NEU ■MIT arch. ▨Harvard ■Wentworth
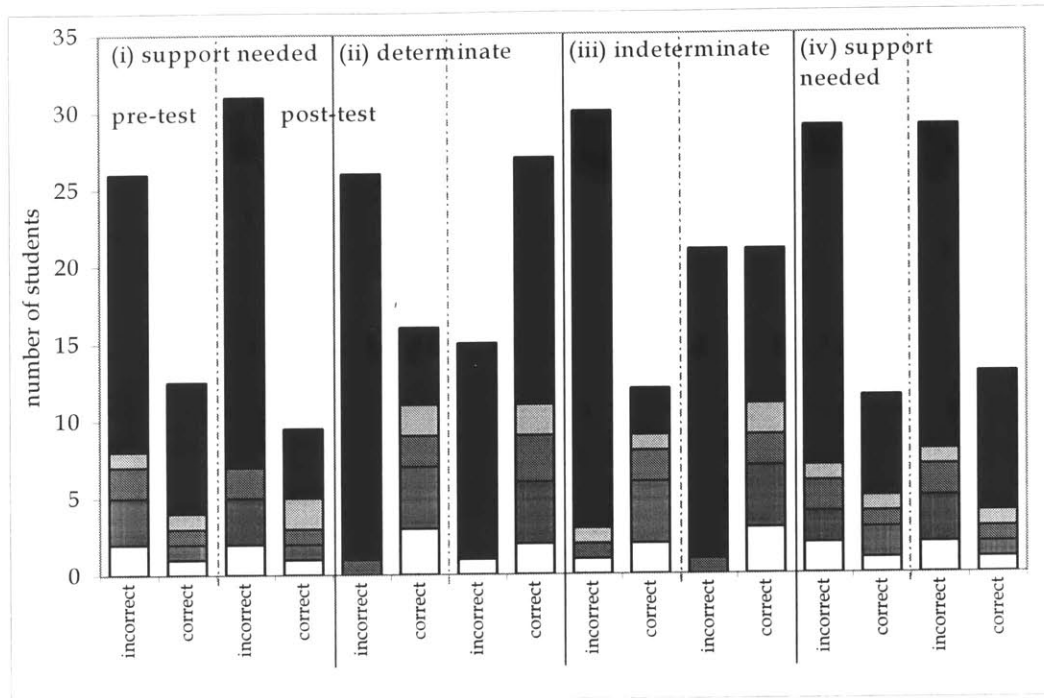
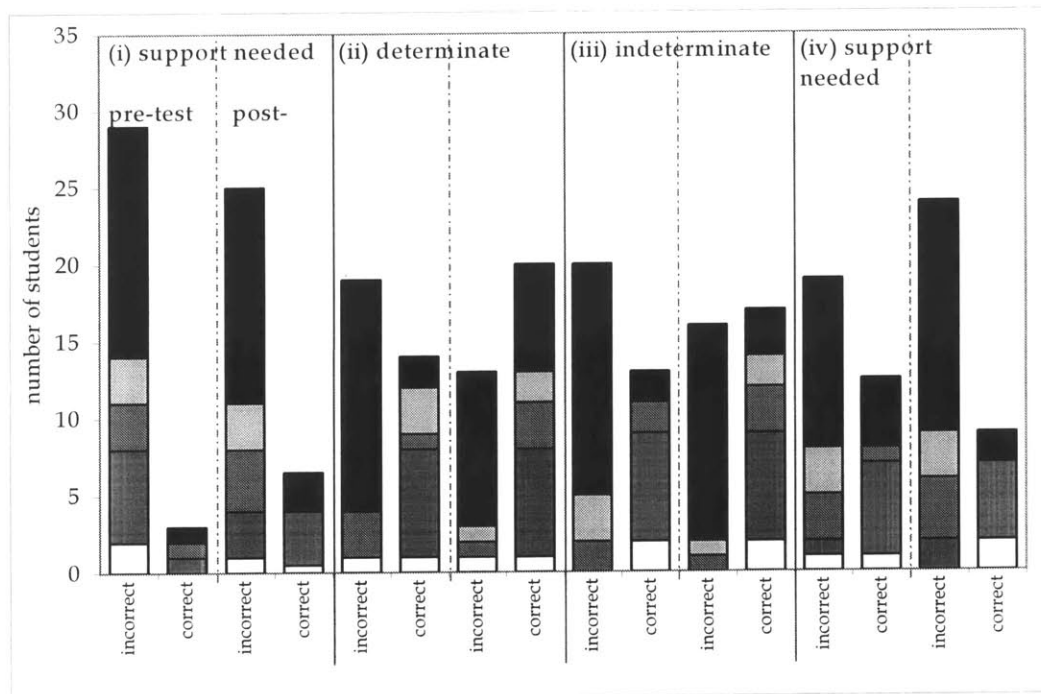**Figure D.2.3   Q2(b) make stable/determinate? Breakdown for each body for *module***

Figure D.2.4   Q2(b) make stable/determinate? Breakdown for each body for *control*

□ MIT eng.   ■ NEU   ■ MIT arch.   ▨ Harvard   ■ Wentworth
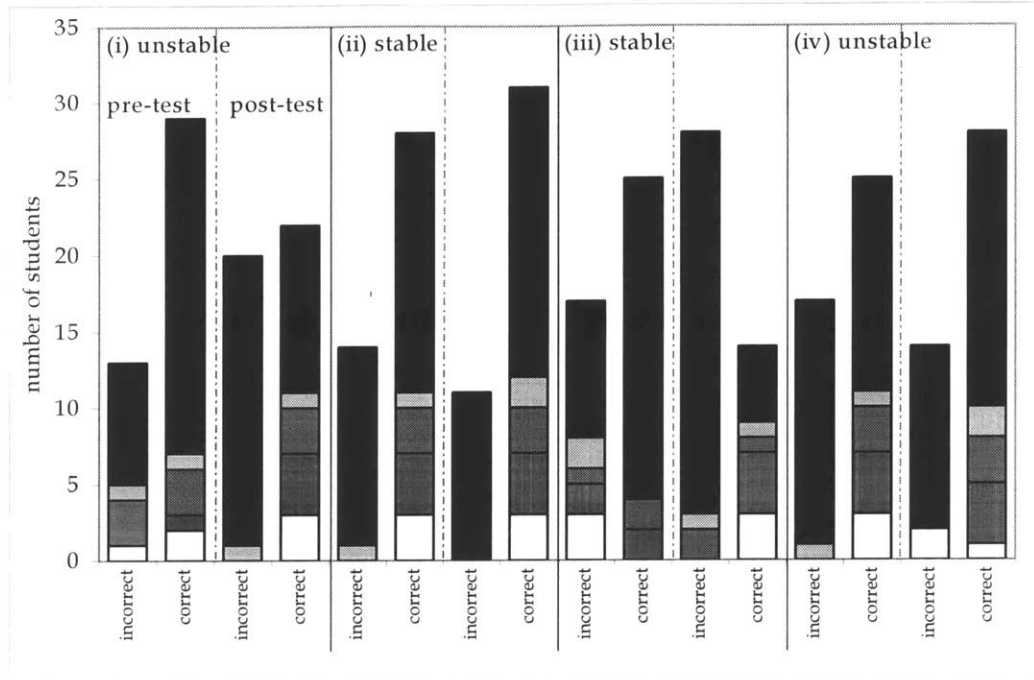
Figure D.2.5   Q3(a) is the assembly stable? Breakdown for each body for *module*

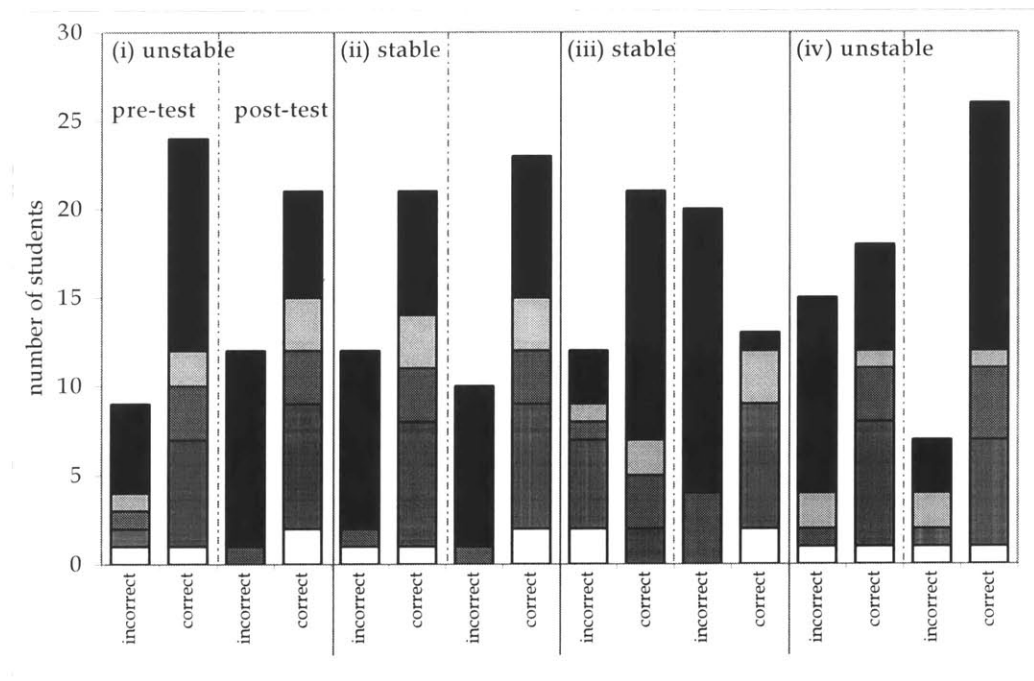

Figure D.2.6   Q3(a) is the assembly stable? Breakdown for each body for *control*

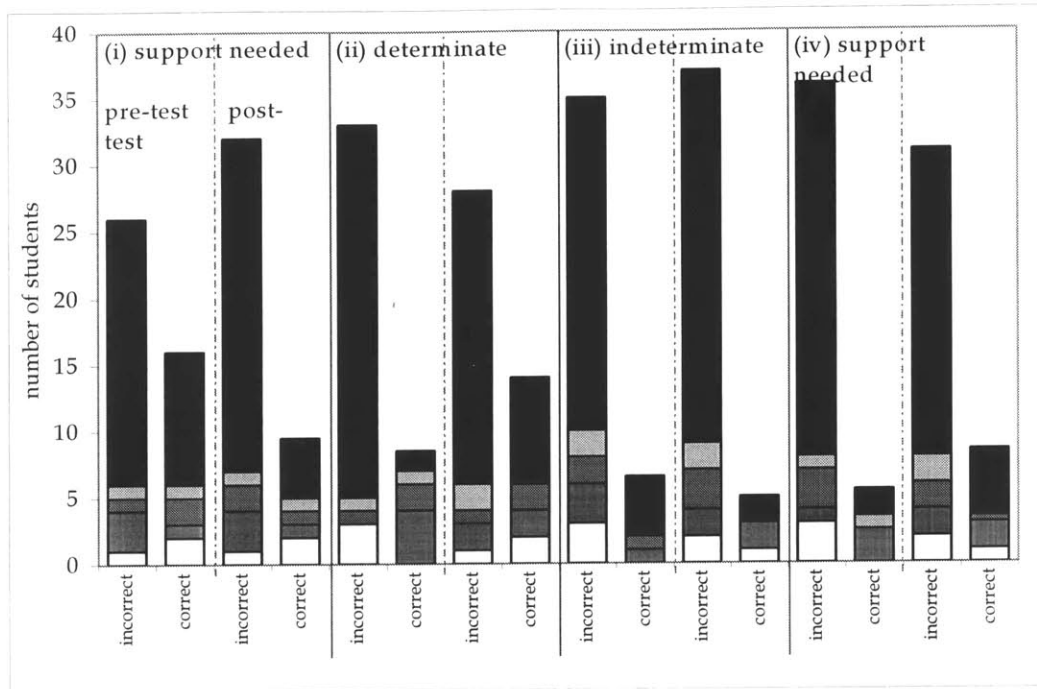□MIT eng. ■NEU ■MIT arch. ▨Harvard ■Wentworth

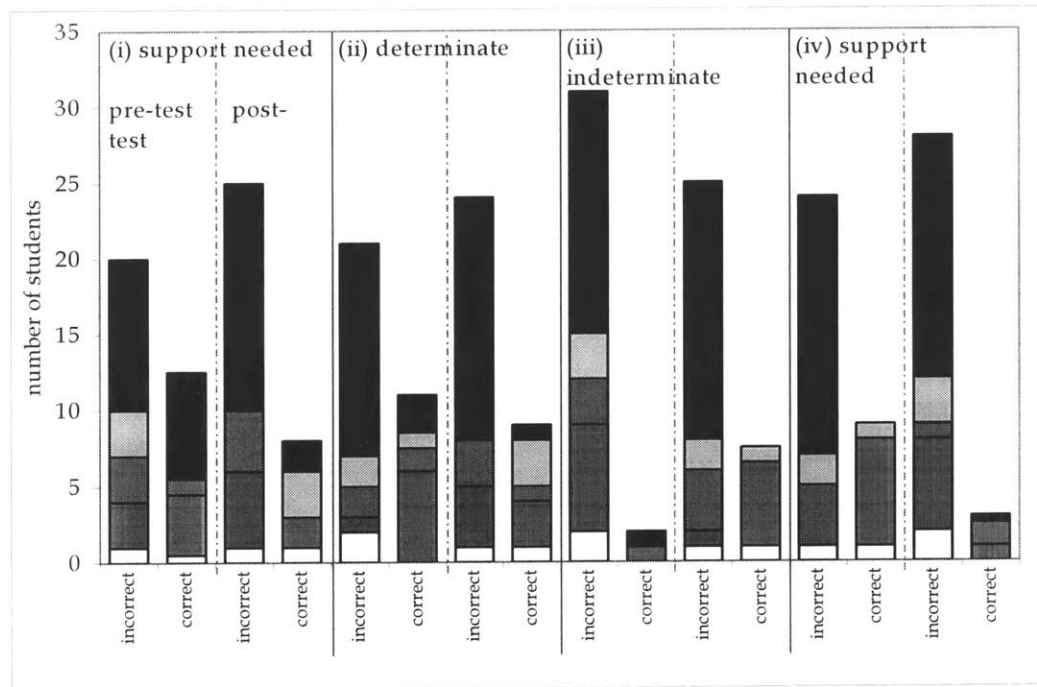Figure D.2.7   Q3(b) make stable/redundancies? Breakdown for each body for *module*

Figure D.2.8   Q3(b) make stable/redundancies? Breakdown for each body for *control*

☐ MIT eng. ■ NEU ▩ MIT arch. ▨ Harvard ■ Wentworth

Table D.2.1   The percentages of students who perform better and worse in each conceptual component of question 4

	module		control	
	worse	better	worse	better
equation				
MIT engineering	*33%**	0%	50%	0%
NEU	75%	25%	*43%*	29%
MIT architecture	33%	0%	25%	50%
Harvard	50%	50%	0%	67%
Wentworth	*3%*	20%	6%	6%
total	*17%*	*24%*	18%	21%
value				
MIT engineering	*33%*	33%	50%	*50%*
NEU	50%	*50%*	43%	43%
MIT architecture	*67%*	33%	75%	50%
Harvard	50%	50%	33%	67%
Wentworth	0%	*7%*	0%	0%
total	*14%*	14%	24%	*18%*
direction				
MIT engineering	67%	33%	*0%*	*100%*
NEU	50%	*50%*	29%	43%
MIT architecture	67%	*33%*	50%	0%
Harvard	50%	*50%*	0%	33%
Wentworth	3%	*13%*	0%	0%
total	17%	*21%*	*12%*	18%
diagram				
MIT engineering	33%	*67%*	*0%*	0%
NEU	25%	*50%*	*14%*	29%
MIT architecture	*67%*	33%	75%	25%
Harvard	50%	50%	*0%*	67%
Wentworth	3%	33%	*0%*	35%
total	*12%*	*38%*	*12%*	33%

***bold italicized** indicates the method to have the maximum improvement or minimum worsening.
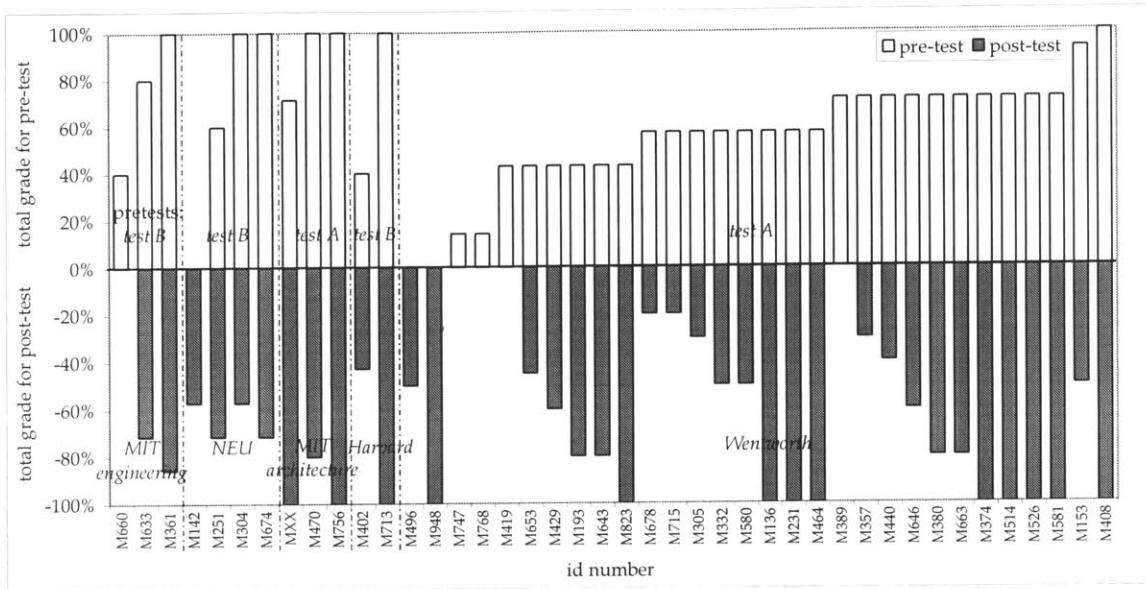
Figure D.2.9 The individual grades from question 6 of the pre- and post-tests for the module
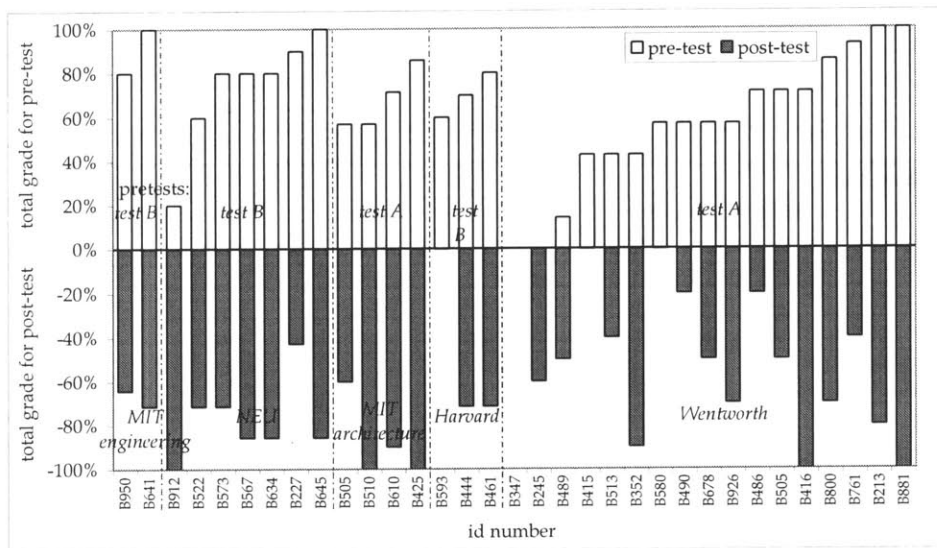
Figure D.2.10 The individual grades from question 6 of the pre- and post-tests for the control

D.3 Results from the Module Interactions
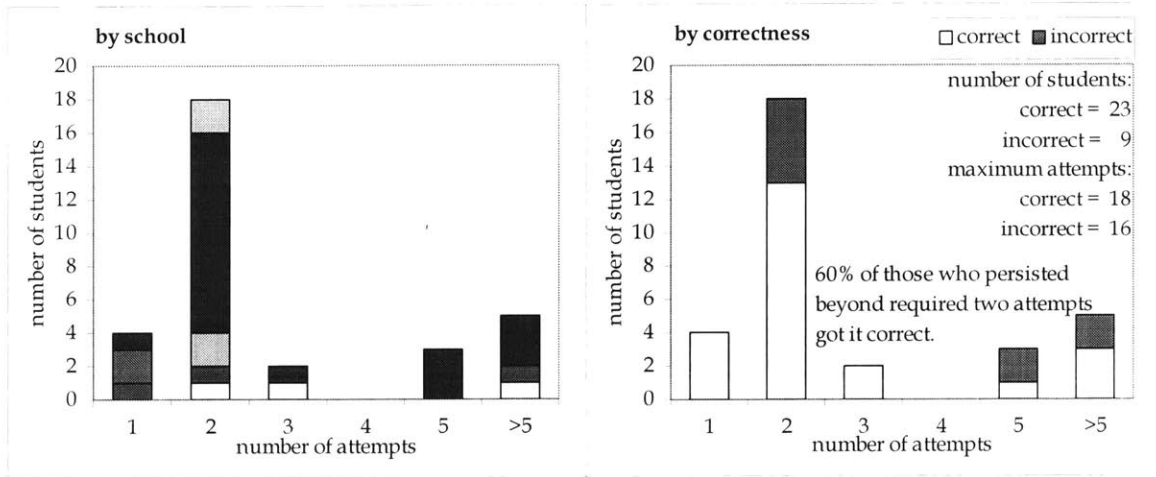
Figure D.3.1   Exercise 1: select examples of rigid body motion
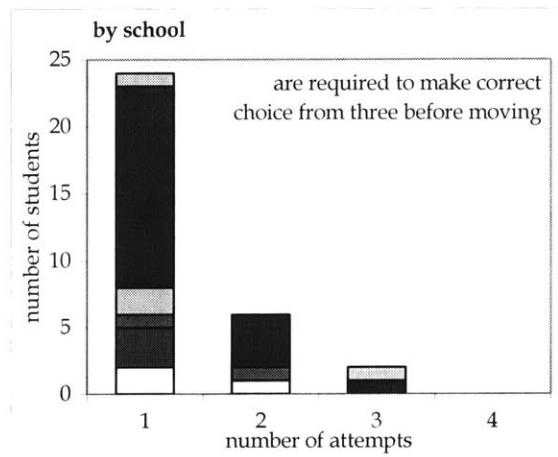
Figure D.3.2   Exercise 2: how to make a rigid body stable?
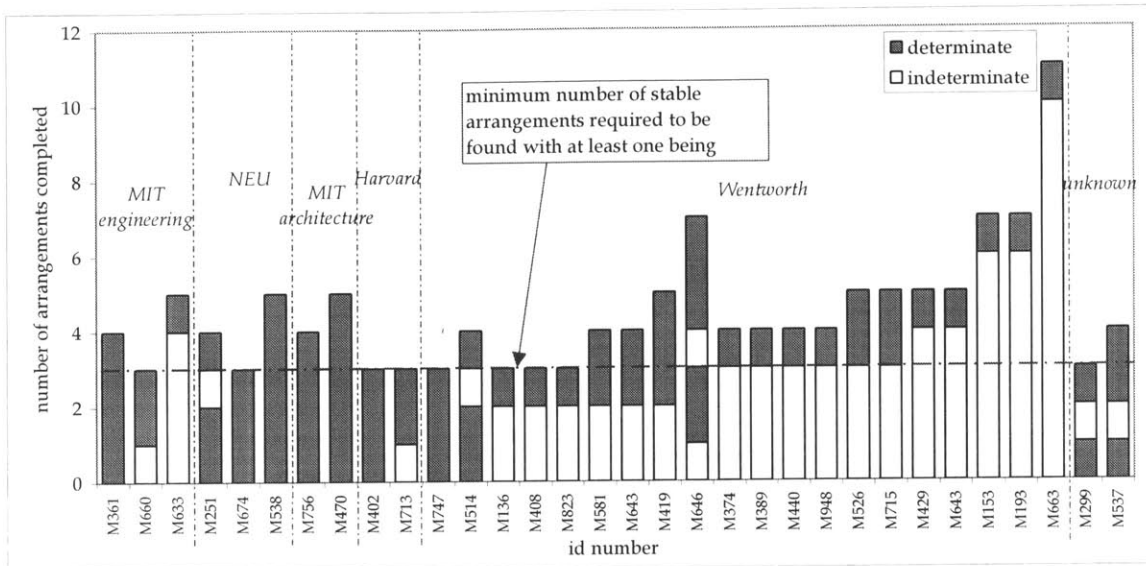
Figure D.3.3   Exercise 3: beam exercise – simulator to stabilize a beam; by type of arrangement
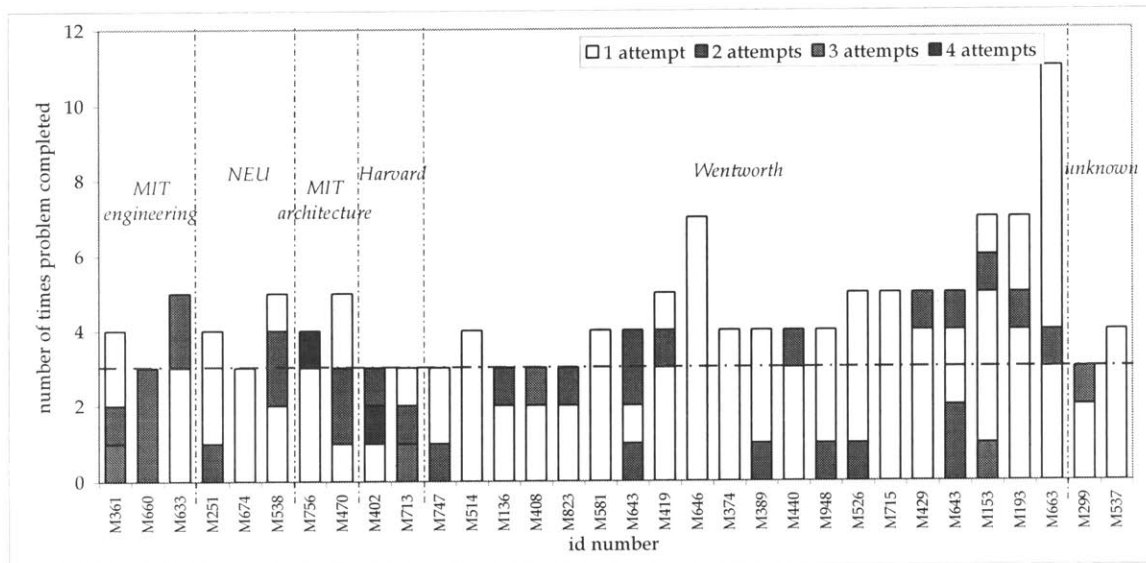
Figure D.3.4   Exercise 3: beam exercise – simulator to stabilize a beam; by number of attempt
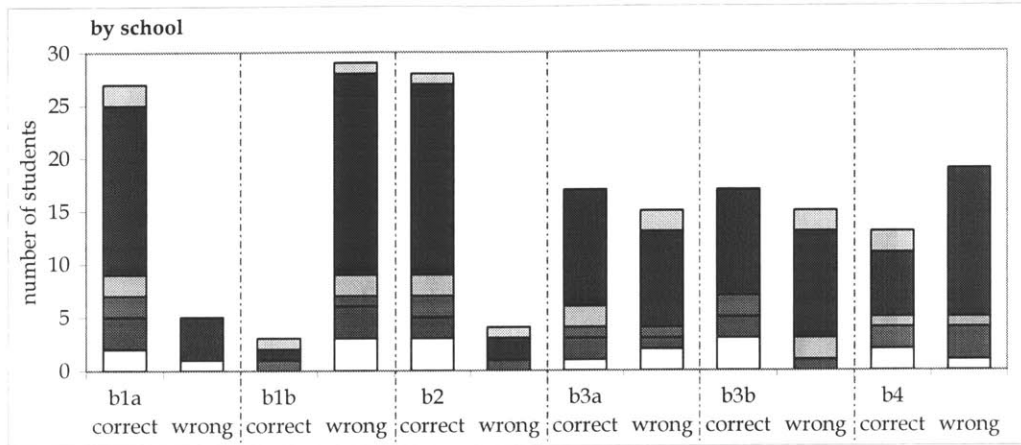
Figure D.3.5   Ex. 4-7: follow-up stability problems, a series of beam arrangements
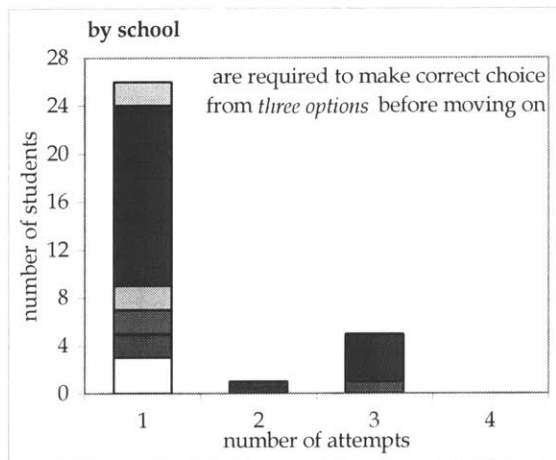
Figure D.3.6   Exercise 8: minimum number of restraints required for 2-d stability
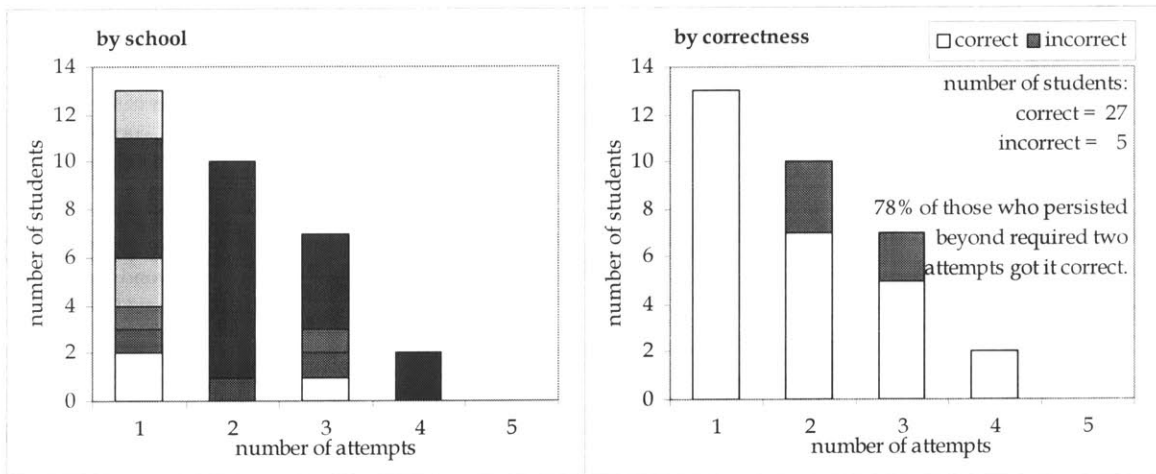
Figure D.3.7   Exercise 9: requirements for 2-d stability

□ MIT eng.   ■ NEU   ■ MIT arch.   ▨ Harvard   ■ Wentworth   □ unknown
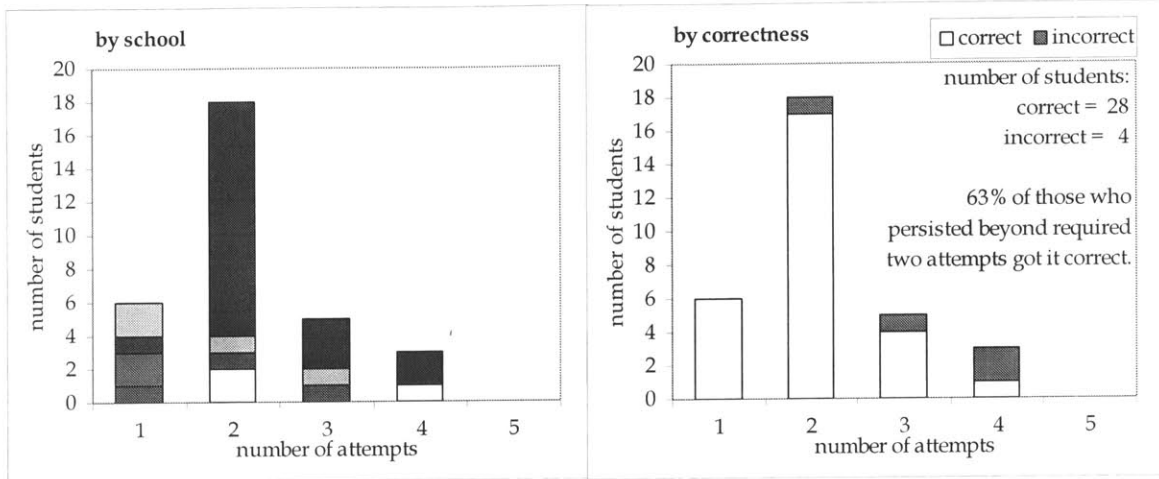
Figure D.3.8   Exercise 10: what is the restraint? ans: pin
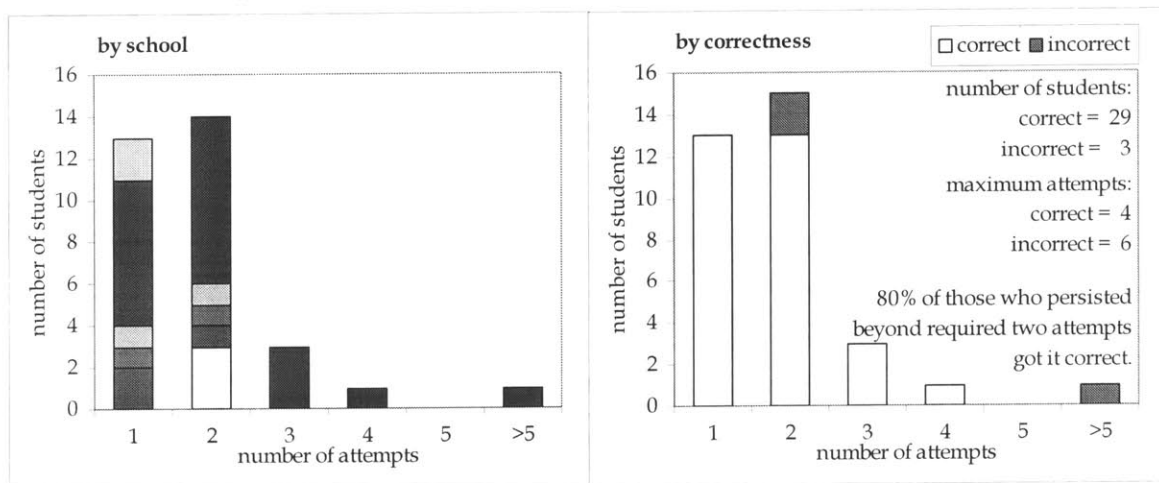
Figure D.3.9   Exercise 11: what is the restraint? ans: roller
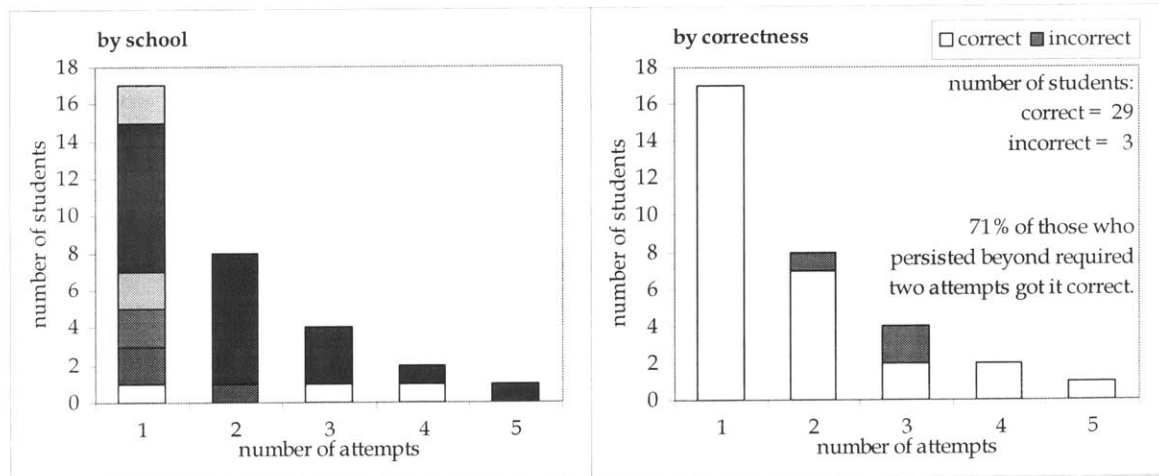
Figure D.3.10 Exercise 12: follow-up practice of "what is the restraint?" (i) ans: pin

□ MIT eng.   ■ NEU   ▨ MIT arch.   ▣ Harvard   ■ Wentworth   ▢ unknown

by school

by correctness □ correct ■ incorrect

number of students:
correct = 28
incorrect = 4

100% of those who persisted beyond required two attempts got it correct.
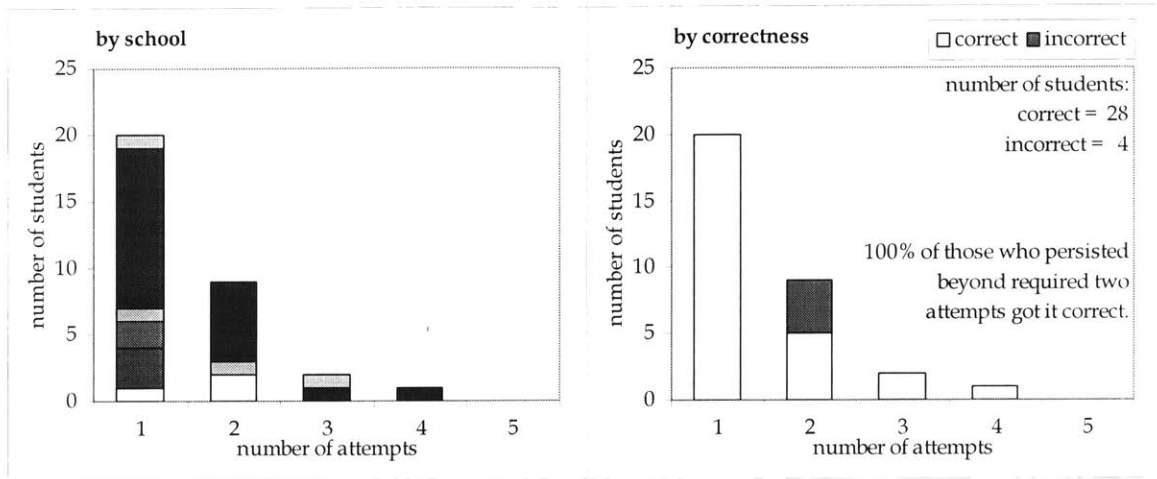
Figure D.3.11 Ex. 13: follow-up practice of "what is the restraint?" (ii) ans: roller

by school

by correctness □ correct ■ incorrect

number of students:
correct = 27
incorrect = 5

100% of those who persisted beyond required two attempts got it correct.
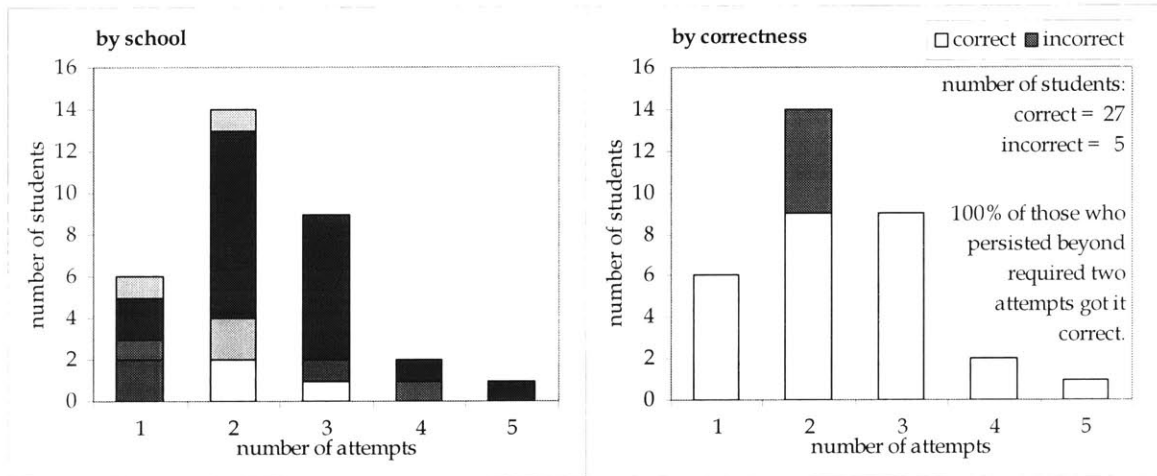
Figure D.3.12 Ex. 14: follow-up practice of "what is the restraint?" (iii) ans: roller

by school

number of students:
correct = 32
incorrect = 0
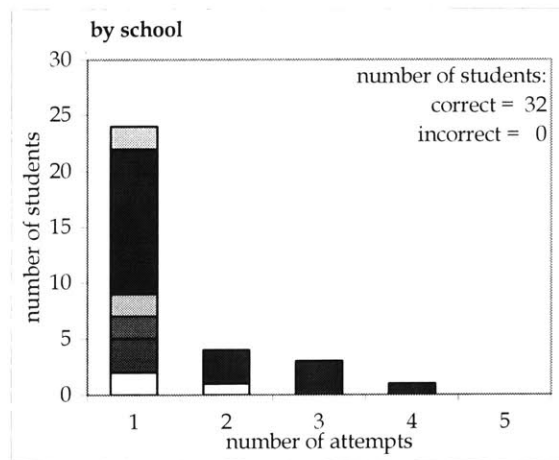
Figure D.3.13 Ex. 15: follow-up practice of "what is the restraint?" (iv) ans: fixed end

□ MIT eng. ■ NEU ■ MIT arch. □ Harvard ■ Wentworth □ unknown
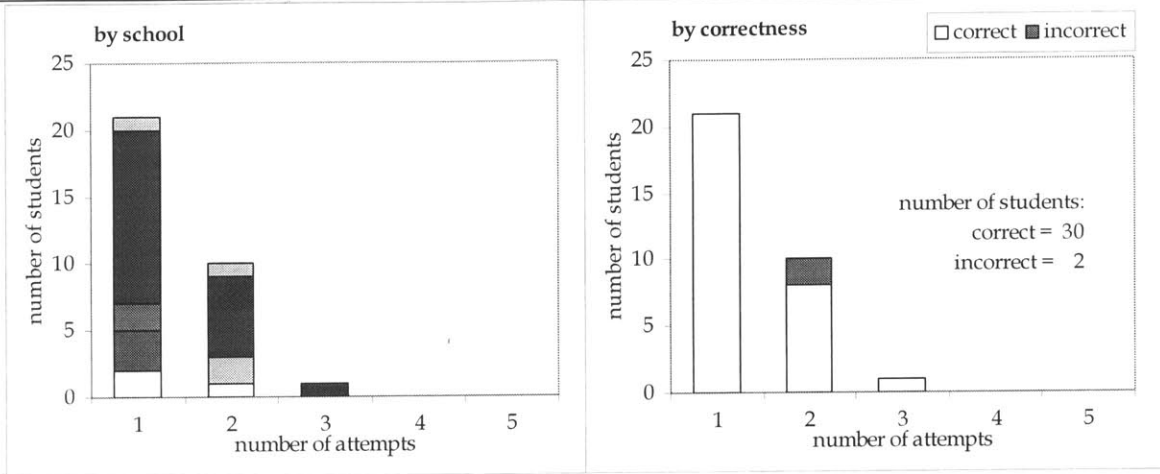
Figure D.3.14 Ex. 16: follow-up practice of "what is the restraint?" (v) ans: pin
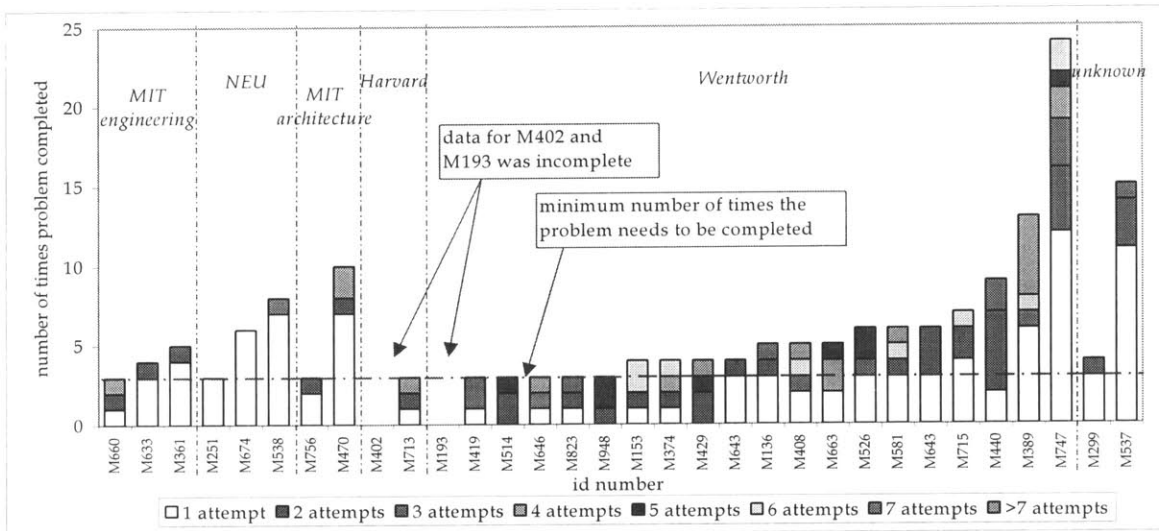
Figure D.3.15 Exercise 17: review exercise – to practice finding determinate arrangements for single bodies
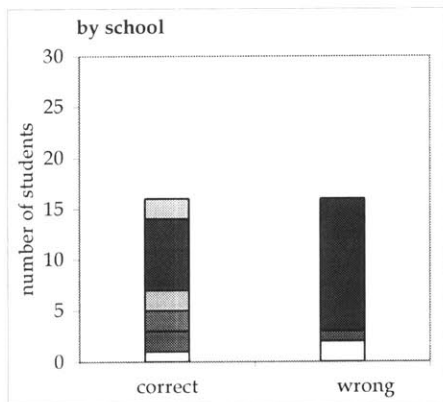
Figure D.3.16 Exercise 18: assembly example, *a simple frame*, is it determinate?
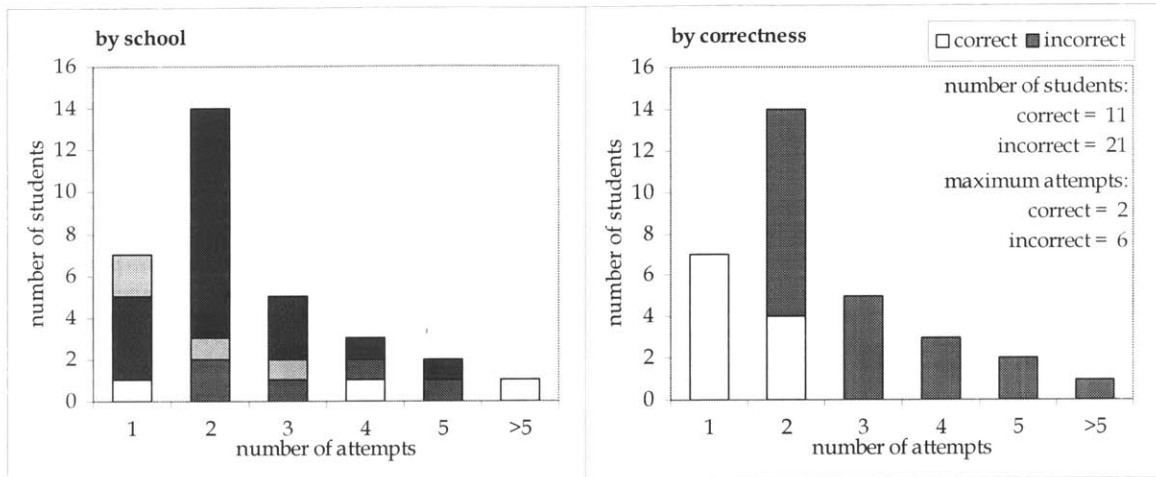
Figure D.3.17 Ex. 19(a): assembly (i), *simple frame,* restraint type of each connection?
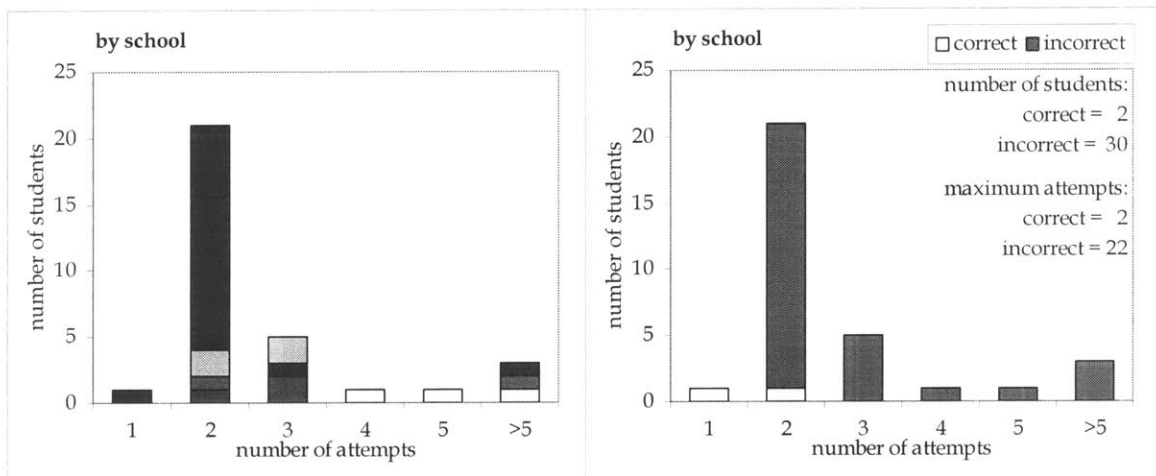
Figure D.3.18 Ex. 19 (b): assembly (i), indicate a load path
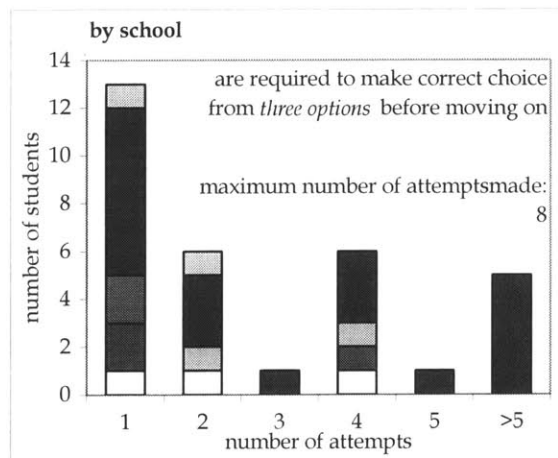
Figure D.3.19 Ex. 19(c): assembly (i), what is its level of redundancy?
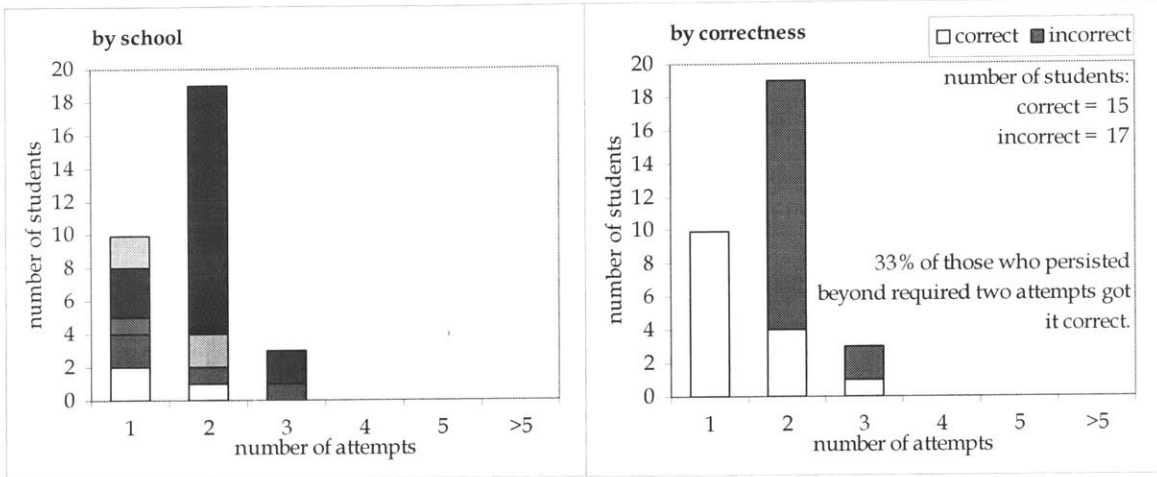
Figure D.3.20 Ex. 20(a): assembly (ii), *simple frame*, restraint type of each connection?
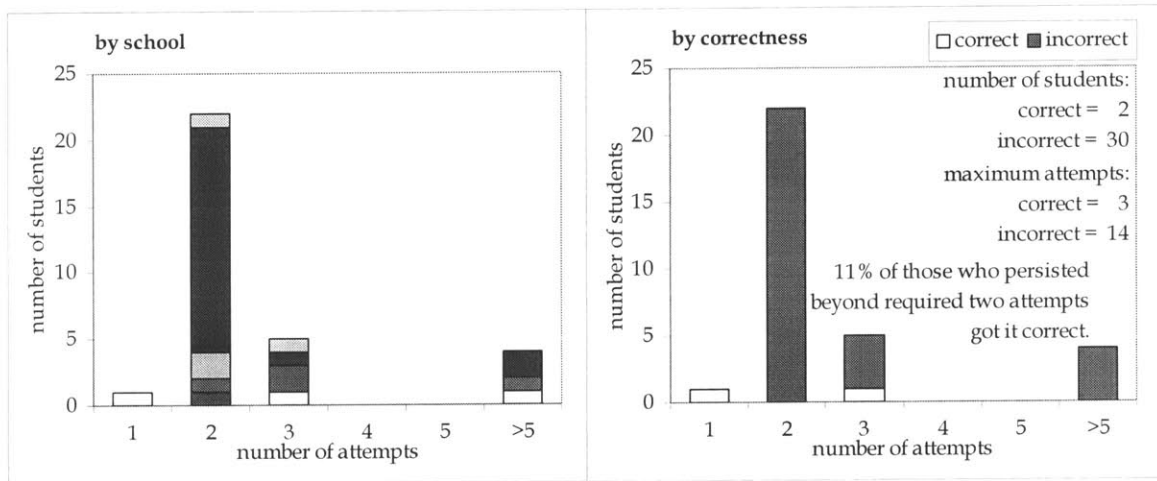
Figure D.3.21 Ex. 20(b): assembly (ii), indicate a load path and redundancy
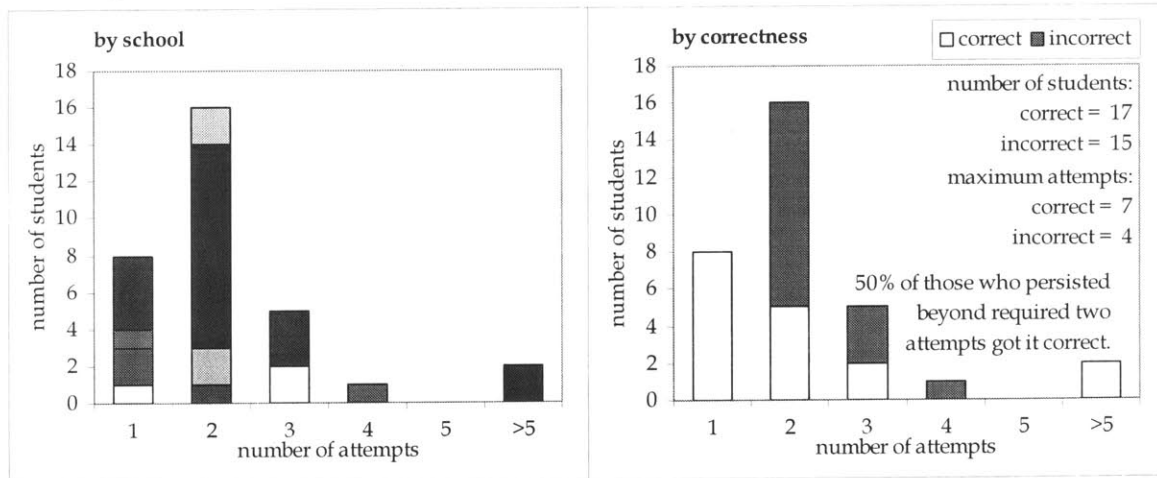
Figure D.3.22 Ex. 21(a): assembly (iii), *portal frame*, restraint type of each connection?
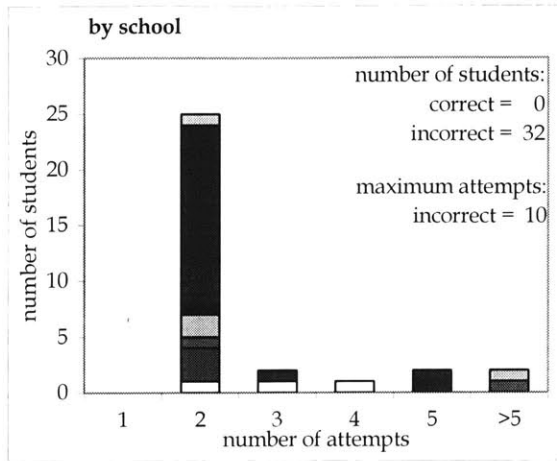
Figure D.3.23 Ex. 21(b): assembly (iii), indicate a load path and redundancy
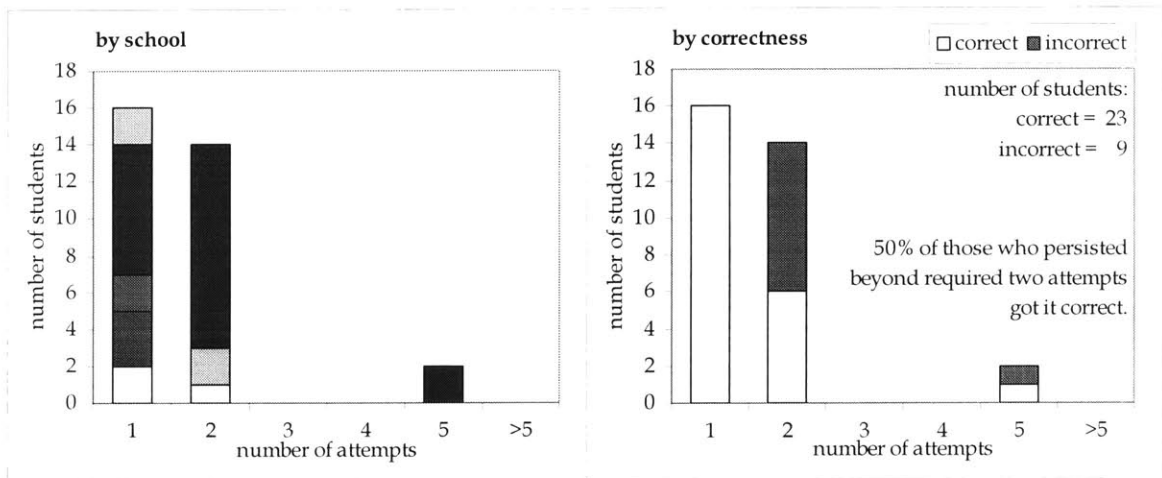
Figure D.3.24 Ex. 22(a): assembly (iv), *angled frame*, restraint type of each connection?
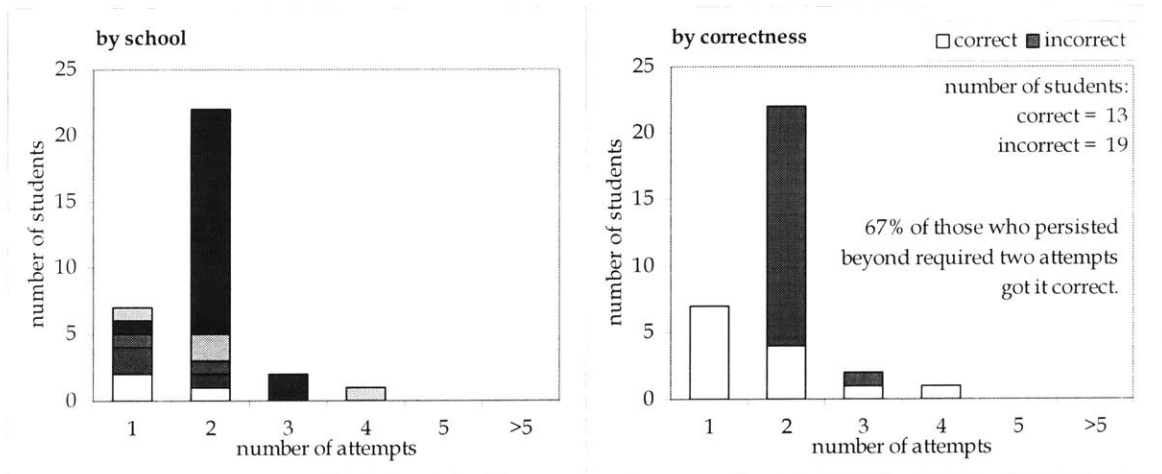
Figure D.3.25 Ex. 22(b): assembly (iv), indicate a load path and redundancy
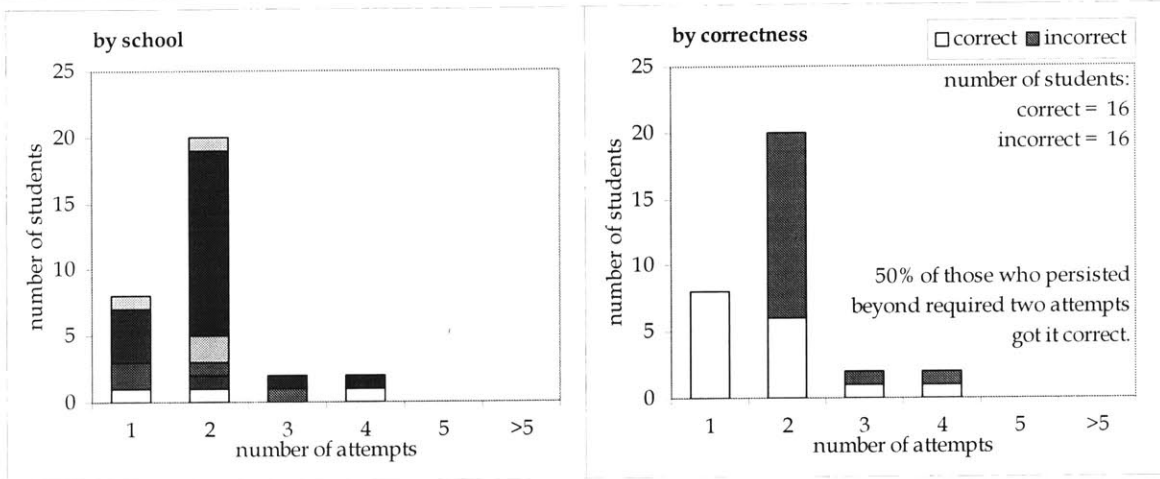
Figure D.3.26 Ex. 23: assembly (v), *braced frame,* indicate a load path and redundancy

Table D.3.1   Student's interaction results for each exercise – correctness, part (i)

exercise	MIT eng.			NEU			MIT arch.		Harvard		unknown	
	M361	M660	M633	M251	M538	M674	M470	M756	M402	M713	M299	M537
1: rbm	✔	✔	✔	✔	✔	✔	✔	✔	X	✔	✔	✔
4(a): b1a	✔	X	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
4(b): b1b	X	X	X	X	X	X	X	✔	X	X	X	✔
5: b2	✔	✔	✔	✔	✔	X	✔	✔	✔	✔	✔	X
6(a): b3a	✔	X	X	X	✔	✔	X	✔	✔	✔	X	X
6(b): b3b	✔	✔	✔	✔	✔	X	✔	✔	X	X	X	X
7: b4	✔	✔	X	X	X	X	✔	✔	X	✔	✔	✔
9: req	✔	✔	✔	✔	✔	✔	X	✔	✔	✔	✔	✔
10: pin	✔	✔	✔	✔	✔	✔	✔	✔	✔	X	✔	✔
11: roller	✔	✔	✔	✔	✔	X	✔	✔	✔	✔	✔	✔
12: pin	✔	X	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
13: roller	✔	✔	✔	✔	✔	✔	✔	✔	✔	X	✔	✔
14: roller	✔	✔	✔	✔	✔	✔	✔	✔	X	✔	✔	✔
15: fixed	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
16: pin	✔	✔	✔	✔	✔	✔	✔	✔	X	✔	✔	X
18: ass. det.	X	✔	X	✔	X	✔	✔	✔	✔	✔	✔	✔
19: ass. 1(a)	✔	X	X	X	X	X	X	✔	X	X	✔	✔
19: ass.1(b)	X	X	X	X	X	X	X	X	X	X	X	X
19: ass. 1(c)	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
20: ass. 2(a)	✔	X	✔	✔	✔	X	✔	✔	✔	X	✔	✔
20: ass.2(b)	✔	X	X	X	X	X	X	X	X	X	X	✔
21: ass.3(a)	✔	X	X	✔	✔	X	X	✔	X	X	✔	✔
21: ass.3(b)	X	X	X	X	X	X	X	X	X	X	X	X
22: ass.4(a)	✔	✔	✔	✔	✔	✔	✔	✔	✔	X	✔	✔
22: ass.4(b)	✔	✔	✔	X	✔	✔	✔	X	X	X	✔	✔
23: ass.5	✔	✔	✔	✔	✔	X	X	X	X	X	✔	✔
% correct	85%	62%	65%	69%	73%	54%	65%	81%	50%	50%	77%	77%

Table D.3.2 Student's interaction results for each exercise – correctness, part (ii)

exercise	M136	M153	M193	M374	M389	M408	M419	M429	M440	M514	M526	M581	M643	M643	M646	M663	M715	M747	M823	M948
1: rbm	✓	X	X	✓	X	X	✓	✓	✓	✓	✓	✓	✓	X	✓	X	X	✓	✓	X
4(a): b1a	✓	X	✓	X	✓	✓	✓	✓?	✓	X	✓	✓	X	✓	✓	✓	✓	✓	✓	✓
4(b): b1b	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	✓	X	X
5: b2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	✓	✓	X	✓	✓	✓
6(a): b3a	X	✓	✓	X	✓	✓	X	✓	X	✓	X	X	✓	✓	X	✓	X	X	✓	✓
6(b): b3b	✓	X	X	X	✓	X	✓	X	✓	✓	✓	X	✓	X	X	X	✓	✓	X	✓
7: b4	✓	X	X	X	X	X	✓	X	✓	X	X	✓	X	X	X	X	✓	✓	X	X
9: req	X	✓	X	✓	✓	✓	✓	✓	✓	✓	X	✓	✓	✓	✓	✓	✓	X	✓	✓
10: pin	✓	X	✓	✓	✓	✓	X	✓	✓	✓	✓	✓	✓	✓	✓	X	✓	✓	✓	✓
11: roller	✓	✓	✓	✓	✓	X	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X
12: pin	✓	✓	✓	X	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	✓	✓	✓	✓	✓	✓
13: roller	✓	X	✓	✓	✓	✓	✓	✓	✓	✓	X	✓	X	✓	✓	✓	✓	✓	✓	✓
14: roller	✓	X	X	✓	✓	✓	✓	X	✓	✓	✓	X	✓	✓	✓	✓	✓	✓	✓	✓
15: fixed	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
16: pin	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
18: ass. det.	X	X	✓	✓	✓	X	X	X	X	X	X	X	✓	✓	✓	X	X	X	X	✓
19: ass. 1(a)	✓	X	X	X	X	X	X	X	X	✓	X	✓	✓	X	X	X	✓	✓	X	✓
19: ass.1(b)	X	X	X	X	X	X	X	X	✓	X	X	X	✓	X	X	X	X	X	X	X
19: ass. 1(c)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	✓	✓	✓	✓	✓	✓	✓
20: ass. 2(a)	✓	X	X	X	X	X	X	X	✓	✓	X	✓	✓	X	X	X	✓	✓	X	X
20: ass.2(b)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
21: ass.3(a)	✓	X	X	✓	X	X	✓	✓	✓	✓	✓	X	✓	X	X	X	✓	✓	X	✓
21: ass.3(b)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
22: ass.4(a)	✓	X	X	X	X	X	✓	✓	✓	✓	✓	✓	✓	X	X	X	✓	✓	✓	✓
22: ass.4(b)	X	✓	X	X	X	X	X	X	✓	X	X	✓	X	X	X	X	✓	X	✓	X
23: ass.5	✓	X	✓	X	✓	X	✓	X	✓	X	X	X	✓	✓	X	✓	X	X	✓	X
% correct	69%	35%	46%	46%	58%	42%	62%	54%	77%	65%	50%	62%	69%	46%	50%	50%	62%	69%	62%	62%

Table D.3.3 Student's interaction results for each exercise – number of attempts, part (i)

exercise	MIT eng.			NEU			MIT arch.		Harvard		unknown	
	M361	M660	M633	M251	M538	M674	M470	M756	M402	M713	M299	M537
1: rbm	3	2	18	1	9	2	1	1	2	2	2	2
stabilize	1	1	2	1	1	1	2	1	1	1	3	1
3: beam (times done)	4	3	5	4	5	3	5	4	3	3	3	4
3: (avge)	1.75	2	1.4	1.25	1.4	1	1.4	1.75	2.33	2	1.67	1
eqn	1	1	1	1	3	1	1	1	1	1	1	1
9: req	1	1	3	3	1	2	3	1	1	1	1	1
10: pin	4	2	2	1	3	2	1	1	2	3	1	1
11: roller	2	2	2	1	1	2	2	1	2	1	1	1
12: pin	1	3	4	1	2	1	1	1	1	1	1	1
13: roller	1	2	2	1	1	1	1	1	1	2	3	1
14: roller	2	3	2	1	1	3	1	4	2	2	2	1
15: fixed	2	1	1	1	1	1	1	1	1	1	1	1
16: pin	1	2	1	1	1	1	1	1	2	2	1	2
17: review (times done)	5	3	4	3	8	6	10	3	1	3	4	14
17: (avge)	1.2	2.33	1.25	1	1.75	1	1.7	1.33	0.5	4.67	1.25	1
19: ass. 1(a)	1	4	6	3	5	4	2	2	3	2	1	1
19: ass.1(b)	5	9	4	2	3	3	2	9	2	2	3	3
19: ass. 1(c)	1	2	4	1	4	1	1	1	2	4	1	2
20: ass. 2(a)	1	2	1	1	1	3	1	2	2	2	1	1
20: ass.2(b)	1	3	14	3	2	3	2	11	2	2	2	3
21: ass.3(a)	1	3	3	1	1	2	4	1	2	2	2	2
21: ass.3(b)	2	4	3	2	2	2	2	10	2	2	2	6
22: ass.4(a)	1	2	1	1	1	1	1	1	2	2	1	1
22: ass.4(b)	1	1	2	2	1	1	1	2	2	2	4	1
23: ass.5	1	2	4	1	1	2	2	3	2	2	2	1
average	1.61	2.45	3.59	1.40	2.09	1.78	1.57	2.57	1.73	1.99	1.69	1.57

Table D.3.4 Student's interaction results for each exercise – number of attempts, part (ii)

exercise	Wentworth																			
	M136	M153	M193	M374	M389	M408	M419	M429	M440	M514	M526	M581	M643	M643	M646	M663	M715	M747	M823	M948
1: rbm	2	5	2	2	6	16	2	5	2	1	2	2	3	2	11	2	5	2	2	2
stabilize	2	2	1	1	1	1	1	1	2	1	1	1	1	1	3	2	1	1	1	1
3: beam (times done)	3	7	7	4	4	3	5	5	4	4	5	4	4	5	7	11	5	3	3	4
3: (avge)	1.33	1.43	1.14	1	1.25	1.67	1.2	1.2	1.25	1	1.2	1	1.75	1.6	1	1.09	1	1.33	1.33	1.25
eqn	1	1	1	2	1	1	3	3	1	1	1	1	1	3	1	1	1	1	3	1
9: req	2	2	3	2	2	1	1	2	3	1	2	1	1	4	2	2	3	2	3	4
10: pin	2	4	2	2	3	2	2	2	2	2	3	2	1	2	2	2	4	3	2	2
11: roller	2	1	1	3	2	6	1	2	1	3	3	2	2	1	1	4	1	2	2	2
12: pin	1	1	2	2	1	2	1	1	5	3	2	4	2	3	2	2	1	1	1	3
13: roller	1	2	1	2	1	1	1	1	1	2	2	1	2	4	3	1	1	2	1	1
14: roller	2	2	2	3	3	3	2	2	5	1	2	2	4	2	1	2	3	3	3	3
15: fixed	1	1	4	1	3	2	1	3	1	1	1	2	1	1	1	3	1	1	2	1
16: pin	1	1	2	2	1	1	2	2	1	1	1	1	1	2	2	3	1	1	1	1
17: review (times done)	5	4	2	4	13	4	3	4	9	3	6	6	4	6	3	5	6	23	3	3
17: (avge)	1.6	3.75	4	3.25	8.77	2.2	2.33	5	2	3	2.67	3.83	1.25	1.5	9	3	0.86	1.71	2	4
19: ass. 1(a)	1	2	2	2	2	2	3	3	5	1	3	1	2	2	4	2	2	1	2	2
19: ass.1(b)	2	2	2	2	2	2	2	2	2	2	3	2	1	2	2	2	2	22	2	2
19: ass. 1(c)	5	4	1	6	1	1	4	1	1	4	2	7	2	2	1	8	7	1	6	2
20: ass. 2(a)	1	2	2	2	2	2	2	2	3	2	2	2	3	2	2	2	1	1	3	2
20: ass.2(b)	2	2	2	2	2	2	2	2	7	2	2	2	2	2	2	2	2	12	2	2
21: ass.3(a)	1	2	2	2	3	2	7	3	2	1	2	2	3	2	2	2	1	1	2	7
21: ass.3(b)	2	2	2	2	2	2	2	2	5	2	2	2	2	2	2	2	3	5	2	2
22: ass.4(a)	1	2	2	2	5	2	2	2	1	1	2	2	1	2	2	2	1	1	1	5
22: ass.4(b)	2	2	2	2	2	2	2	2	3	2	2	2	2	2	2	2	2	3	1	2
23: ass.5	2	2	1	2	2	2	1	2	1	2	2	2	3	2	2	2	4	2	1	2
average	1.69	2.14	1.92	2.18	2.48	2.56	2.07	2.23	2.49	1.74	1.99	2.08	1.87	2.09	2.61	2.35	2.12	3.09	2.01	2.36

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