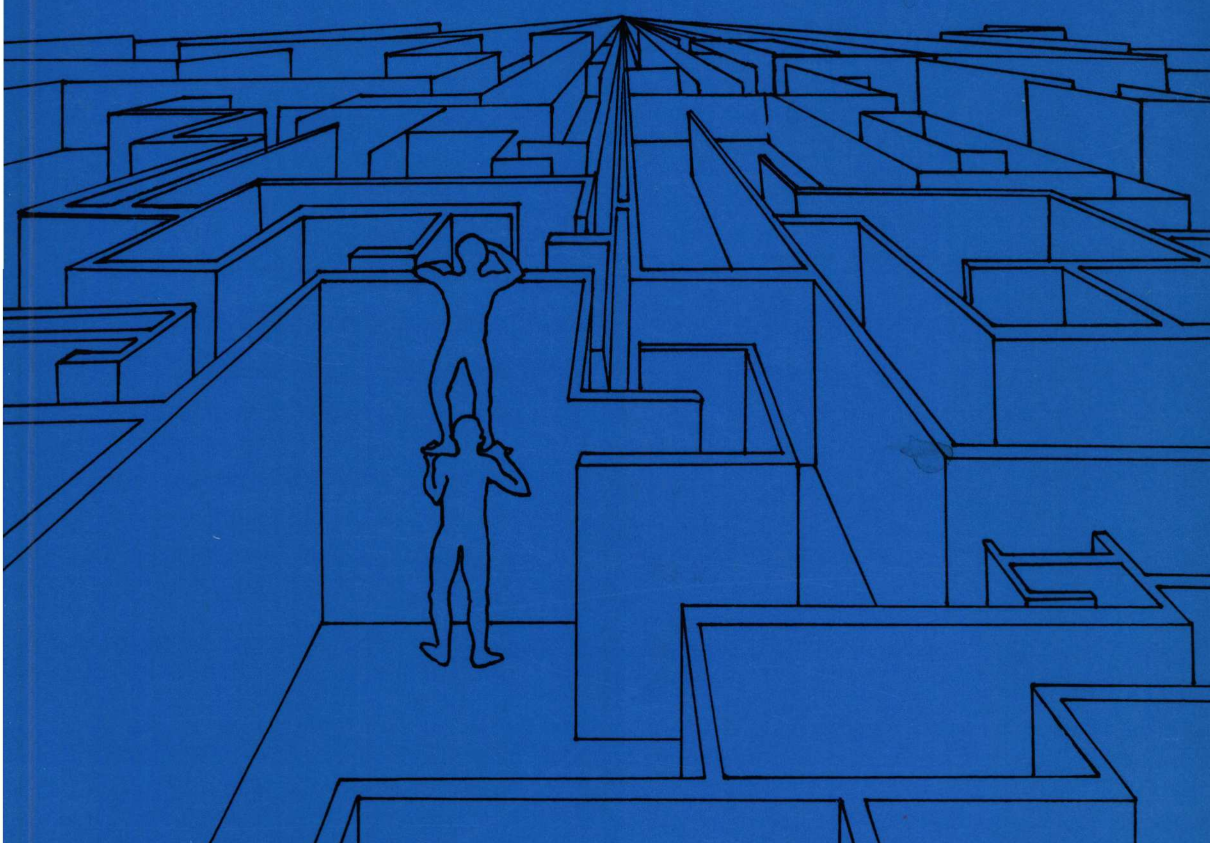
# Cognitive Tools

## Two exercises in non-directive support for exploratory learning



Anja van der Hulst

# Stellingen

behorende bij het proefschrift

*"Cognitive Tools*
*Two excercises in non-directive support for exploratory learning"*

Anja van der Hulst

1. Exploratief leren is niet eenvoudig.

2. In de mens-computer interactie is lang als gegeven aangenomen dat sturing ten koste gaat van flexibiliteit, het is echter weldegelijk mogelijk een omgeving zo in te richten dat deze gedrag op een natuurlijke wijze stuurt maar daarbij nog steeds volledige vrijheid van handelen laat.

3. Gedrag wordt sterk gestuurd door conventies, conventies kunnen dus gebruikt worden om gedrag te sturen.

4. De huidige instructie-ontwerptheorie, die met name gericht is op gebruik door menselijke ontwerpers, is veelal te globaal en tevens te ambigu om te kunnen dienen als basis voor computer gebaseerde systemen voor instructie-ontwerp.

5. Een kennistechnologische aanpak van instructietheorie ontwikkeling waarbij gegeneraliseerd wordt vanuit het handelen van experts, kan leiden tot meer specifieke theorie die tevens beter aansluit bij het denken van de instructie-ontwerper. De kennis- en informatie technologie bieden daarnaast gereedschappen voor operationalisatie van theorie en kunnen daarmee een belangrijk hulpmiddel zijn in het streven naar minder ambigue theorie.

6. Bij methodieken die zijn ontstaan als reactie op het 'early prototyping' moet er voor worden gewaakt dat een verregaande vorm van conceptualisatie niet leidt tot 'late prototyping' waarbij het beschikbare budget verbruikt is voordat het tot een gebruikersevaluatie is gekomen.

7. Om het World Wide Web als medium uiteindelijk bruikbaar te houden zal het noodzakelijk zijn vormconventies op te leggen aan op het Web te plaatsen documenten.

8. In een rationele omgeving is het soms moeilijk te accepteren dat een onderliggende oorzaak van een probleem niet te vinden is terwijl de remedie bekend is. Wellicht is dit de reden dat in de academische wereld het sick building probleem zo weinig voortvarend wordt aangepakt.

9. Het fileprobleem vraagt om een onconventionele oplossing, om die reden alleen al zou de Nederlandse Vereniging voor Human Powered Vehicles gesubsidieerd moeten worden door het ministerie van VROM.

10. Zonder recepties, borrels, feesten en partijen is full time telewerken geen haalbare kaart.

11. De waarde van een promotie is niet altijd even duidelijk. Echter een van de verworvenheden van de kersverse doctor is wel dat zij na het verwerven van haar titel met een beslist hogere frequentie aangeschreven zal worden met "geachte heer".

# Samenvatting


Informatietechnologie maakt veel mogelijk, de introductie ervan betekent echter niet noodzakelijk dat het leven er eenvoudiger op wordt. Waar voorheen het verwerven van informatie een probleem kon zijn, is momenteel het verwerken van een overdaad aan informatie eerder problematisch. Het World Wide Web bijvoorbeeld, biedt een rijkdom aan informatie, wat niet wil zeggen dat deze informatie zonder meer bruikbaar is. Informatie op het Web is in hoge mate ongestructureerd, vaak onvolledig en zelden toegespitst op de lezer. Het vraagt dan ook nogal wat vaardigheid om al explorerend uit de beschikbare fragmenten de gewenste kennis te extraheren. De hiervoor noodzakelijke verwerkingsvaardigheden zijn niet zonder meer een ieder gegeven. Onderzoek op het gebied van exploratief leren brengt vaak een chaotische, weinig effectieve werkwijze aan het licht. Een observatie is dat lerenden snel afgeleid worden door beslist interessante zijwegen die ook weer hun niet minder interessante vertakkingen hebben en uiteindelijk gedesoriënteerd het systeem verlaten. Dergelijk chaotisch gedrag is niet alleen geconstateerd bij exploratie in hypermedia-omgevingen zoals het World Wide Web maar ook in simulatie-omgevingen. In deze omgevingen dient de lerende door systematische manipulatie inzicht in de aard van een gesimuleerd verschijnsel te verwerven. Onervaren gebruikers zijn geneigd vooral veel variabelen tegelijk te manipuleren om tenslotte af te haken voordat ze daadwerkelijk inzicht in het aan de simulatie ten grondslag liggende model hebben verworven.

Het zal duidelijk zijn dat er een taak ligt voor onderwijs. Steeds meer zal de nadruk van het onderwijs moeten verschuiven van het verwerven van kennis naar het verwerven van kennisverwervingsvaardigheden. Dat wil niet zeggen dat er geen verbetering gezocht kan worden in het eenvoudiger en beheersbaarder maken van de verwerkingstaak zelf. Dit laatste was het streven van het promotie-onderzoek. De intentie was te komen tot zogenoemde 'cognitive tools', instrumenten die het leven in een complexe informatiewereld eenvoudiger moeten maken, maar daarbij tevens zo veel mogelijk van de voordelen van exploratie weten te behouden. Dit was een niet onbelangrijke eis, daar de verwachting bestaat dat door middel van exploratie actief verworven kennis tot diepere, meer stabiele kennisstructuren aanleiding kan geven.

In het hier beschreven onderzoek werden twee vormen van ondersteuning ontworpen en ondergebracht in zogeheten 'auteursystemen', instrumenten die auteurs van onderwijsmateriaal de hand bieden om voor hun specifieke domein ondersteuning te realiseren. In een eerste vorm werd exploratiegedrag gemanipuleerd met behulp van een grafische representatie van de structuur van een hypermedia document. Dit grafisch overzicht was zo vormgegeven dat een 'conventionele' wijze van verwerking van nature aanleiding zou geven tot een optimaal exploratietraject. Hierbij werd gebruik gemaakt van de voorspelbaarheid van leesrichting in enkele bouwstenen van grafische representaties. Deze representatie was een pure vorm van niet-directieve ondersteuning omdat de exploratievrijheid in geen enkel opzicht ingeperkt werd maar de inrichting van de omgeving tot gewenst gedrag aanleiding bleek te geven. Een experimentele studie bracht aan het licht dat de grafische representaties het leren zeker in positieve zin kunnen beïnvloeden. De vraag is echter of het leereffect terug te voeren is op de geconstateerde meer optimale vorm van exploratie of dat het een meer direct effect is van het beschikbaar hebben van een goed grafisch overzicht.

Een tweede vorm van ondersteuning werd geimplementeerd in de vorm van een instrument waarmee complexe simulatiemodellen omgewerkt kunnen worden naar een serie modellen die gradueel in complexiteit toenemen of verschillende perspectieven op een model tonen. Het idee was hier de exploratieruimte zodanig in te perken dat deze net beheersbaar zou worden. Experimenten brachten aan het licht dat ook deze vorm positief kan uitwerken mits er geen meer sturende vormen van ondersteuning aanwezig zijn.

Het resultaat van het onderzoek is een inventarisatie van eisen waaraan ondersteuning voor exploratief leren moet voldoen en enkele realisaties die naar oordeel grotendeels voldoen aan deze eisen. Bij deze ondersteuning speelt het beheersbaar maken van complexiteit een grote rol, ofwel door het aanbieden van zinvolle representaties, of door het focusseren van de aandacht van de gebruiker door het inperken van de exploratieruimte. Hopelijk is hiermee een aanzet gegeven tot de verdere ontwikkeling van 'cognitive tools', gereedschappen die het leven in de huidige complexe informatiemaatschappij wat eenvoudiger kunnen maken.

# CV

Anja Hilda van der Hulst was born on the 29th of May 1966 in Hengelo, The Netherlands. In 1984 she finished her pre-university education to start her studies in educational science and technology at the University of Twente. After a project on domain representation techniques for ITSs for the Dutch Open University, she received her masters degree in March 1990.

Her working career started promising, she delivered papers for quite some years. While at the university, student assistantships got her more into writing papers. A next career move was the writing of this book. This endeavor took place while employed by the University of Amsterdam to work on methodological issues in ITS. In addition, two years later she got involved in the SMISLE project. This project was an EC funded cooperation between industry and academia that resulted in an authoring system for simulation based learning environments. In December 1995 she joined the training and education R&D group of the Dutch research institution TNO-FEL. While at the UvA or TNO, her mission was and will remain the inventing of things that make the learner smart. Just recently her career hit the fast lane. European and world titles in Human Powered Vehicles got her and her recumbent into the papers.

# COGNITIVE TOOLS

Two exercises in non-directive support for exploratory learning

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Universiteit van Amsterdam,
op gezag van de Rector Magnificus
prof. dr P.W.M. de Meijer
ten overstaan van een door het college van dekanen ingestelde
commissie in het openbaar te verdedigen in de Aula van de Universiteit
(Oude Lutherse Kerk, ingang Singel 411, hoek Spui),
op vrijdag 18 oktober 1996 te 13 uur.

door

ANJA HILDA VAN DER HULST

geboren te Hengelo (Ov)

Promotor: Prof. dr B.J. Wielinga
Co-promotor: dr A.J.M. de Jong

Faculteit der Psychologie
Universiteit van Amsterdam

Promotiecommissie:

| | |
|---|---|
| Prof. dr D.M. Merrill | Utah State University |
| Prof. dr J.M. Pieters | Universiteit Twente |
| Prof. dr J.J. Elshout | Universiteit van Amsterdam |
| Prof. dr J.G.W. Raaijmakers | Universiteit van Amsterdam |
| Prof. dr J.A.P.J. Breuker | Universiteit van Amsterdam |
| Dr R. de Hoog | Universiteit van Amsterdam |

Illustratie voorkant: Pascale Levebvre

The research reported here was carried out in the course of two research projects by the name of SMISLE and MIOS. The SMISLE project was partially funded by the DELTA Program of the Commission of the European Communities (project D2007). Partners in SMISLE were the universities of Twente (NL) and Amsterdam (NL) and the industrial partners Marconi Simulation (UK), Framentec (FR), and ESI(FR). Test sites in SMISLE were IPN-Kiel (G) and the university of Murcia (SP). The MIOS project was funded by the 'Profileringsfonds' of the University of Amsterdam.

To my parents

# Contents

# Preface

Each PhD trajectory has its own particular challenges. Looking back on mine, I am more than happy to be able to say that in the end 'things have turned out ok'. I'm indebted to those who were crucial in their support in making things turn out as they did.

One of the people who made a difference was Ton de Jong. Guide from the very beginning right up until our marathon through all those pages of manuscript. Ton, thanks for not giving up, I know this one hasn't been easy on you as well. Your example will remain an inspiration for the coming years. Bob Wielinga, PhD supervision turned out to be a major exercise in travel back and forth between odd locations. Bob, I learned a lot during my years at SWI, you have been a major factor in that. Also, thanks for being one of the major creators of a group that provided a perfect combination of good science and equally good fun.

Many people from this group contributed to this thesis. By conducting studies together, as with Paul Kamsteeg, Yvonne Barnard, Bert Bredeweg and Jacobijn Sandberg. Nobody will ever beat me again in matters in tidal elevation, balances and thermodynamics. Others, by sharing their scientific and miscellaneous matters during the Solo experiences, or by just being there when needed, thanks Lenie Zandvliet and Saskia van Loo.

EC based research consortia come in different qualities. My, maybe not entirely objective, judgement was that the SMISLE team was TOP of the bill. Good cooperation, well tested useful products, and lots of air miles. Many participated in this top team, in this context I can only give a special mention to a few of them. Robert de Hoog and Michiel Kuyper with whom I did a lot of work together and who, to enable that, provided a highly dynamic research environment. Mischa van Rijswijk for his work in evaluation and experimentation. Wouter van Joolingen and Janine Swaak, who, with Ton, made me aware of the fact that experimentation is not just hard work but can be exciting as well. Finally, David Scott, André Alusse, and Jean Marc Loingtier, you might be interested to know that I recently received my first job offer to work as a SmallTalk programmer. Indeed, some employers overreact to a tight labor market ;-)).

All students that participated in the experiments are gratefully acknowledged. Certainly, to make learning beneficial, some have to suffer first. Then, Dr David Merrill's ID2 team with which I spent 3 months at Utah State University. Good ideas, nice tools and cool biking. It is good to see the results of years of work at last hit the market. Hope that it will become the basis for a true leap forward in instructional design. Three months in the US, however, was not enough to make my written English entirely perfect. Lynda Hardman, thanks for the numerous corrections in most chapters of this thesis and for making the writing of English certainly more fun.

Nienke, Jannie, Joost B., Radboud, Antoinette, Monique, Johan, Wiepke, Joost W. and Andre, the hospitality was great! Having to leave the faculty's sick building half way through the PhD exercise would no doubt have meant an end to that same exercise if the department of AI and Law had not hosted me for the final period of almost three years. Thanks again for the so highly appreciated atmosphere.

Family and friends, what can I say. I can only apologize for being so caught up in every day things. Next year I'll certainly try to send birthday cards ;-). The last to be mentioned here is certainly not the least, Jan, a great partner in life and work. In the future I certainly hope we will be able to spend less time together behind our respective screens.

Then, the book is finished, the house, well almost. A new scientific challenge and most exiting plans are waiting (just watch your sports pages ;-), time has come for life after the PhD.

# Introduction 1

Exploratory learning in unstructured environments is learning it the hard way. The learner who is confronted with, for example, a complex microworld, faces a difficult task. Where expository media provided the learner with a super-imposed curriculum structure, unstructured learning environments leave the regulation of learning in the hands of the learner. Yet, the gain of proper exploration could be substantial. Knowledge resulting from exploratory learning is thought to be more stable and deeply rooted than if acquired through more passive ways of learning. But, as we will argue in this chapter, few learners can handle the cognitive demands made upon them by environments for exploratory learning. Fruitful exploration requires an extensive amount of self regulation of the learning process, for some too much to handle.

Norman's (1993; 1988) solution for support is almost too trivial; if a task is too demanding, then change the task. The question tackled in this thesis was how to design environments so that the task of exploration remains manageable. The mission, therefore, was to reduce the 'costs' of exploratory learning, yet retain as much of the benefits as possible. That is, an environment should be designed so that it allows active engagement and thus enables learners to tailor the learning process to their own needs, yet protects them from getting lost. Moreover, the environment should tacitly guide them to explore in a beneficial way. Hence, learners had to be offered the cognitive tools to 'help them to help themselves'.[1] All in all, in the tradition of Norman, the ambition was to create 'things that make the learner smart'.

## 1.1 Exploration, a demanding task

Exploratory learning seems to fall short of expectations expressed with respect to its effects. Exploration should result in a more active engagement in the learning process, make learning a richer and more challenging experience (see e.g. Marchionni, 1988; Goodyear *et al.*, 1991). In fully unstructured environments, learners need to find their way in an information or model space by actively setting their own learning goals and finding methods to achieve those goals. Active engagement in the learning process was claimed to encourage reflective thinking (Norman, 1993). Reflection is an important trigger for the painful but essential process of restructuring, that is, the adjustment of cognitive structures when old structures are found to be inadequate. In addition, active engagement is perceived to be instrumental to the activation of the learner's own knowledge. This activation is generally assumed to facilitate assimilation of new knowledge into the current cognitive structure. An enhancement of assimilation and restructuring should be reflected in results. Indeed, exploration is said to result in more deeply rooted knowledge (Wittrock, 1966; Bruner, 1974) and enhanced transfer (Bruner, 1974). Besides, frequent experience with regulation is argued

[1] There is nothing really new here, 'help me to do it myself' is a motto of the work of Maria Montessori of the beginning of this century (as still published in e.g. Montessori, 1973)

to result in the acquisition of regulatory skills (Marchionni, 1988). Finally, several contended (see e.g., Dekkers & Donatti, 1981; Alexander *et al.*, 1994) that active engagement would readily lead to enhanced motivation.

Nevertheless, current practice in exploratory learning, both in simulation and hypertext environments, tends to be disappointing. Studies investigating learning with hypermedia compared to learning with linear presentation formats have shown no effects (see e.g. McGrath, 1992; Beishuizen *et al.*, 1994) or even detrimental effects of the use of the hypertext format (McKnight *et al.*, 1990; Rada & Murphy, 1992). For simulations a similar observation can be made. De Jong et al. (1993b) listed several studies that failed to find any advantage of simulation-based learning.

A major barrier for fruitful learning by exploration in hypertext, as signaled by (Conklin, 1987; Foss, 1987; Marchionni, 1988; Rouet, 1990) is that people, while exploring material, easily 'get lost in hyperspace'. Hypertext offers a large degree of freedom and users appear to have trouble handling this freedom. Distraction is one problem. Foss (1987) mentions in this respect the 'art museum phenomenon'. Having spent long days wandering around and gazing at paintings, some may recall an abundance of details but still have failed to discover the main lines.

Museums or hypertext can be explored in many ways and it requires a clear target to be able to decide how the environment could be explored best. Considering the museum example, being interested in influences on impressionists (the target), a plan would be to study the impressionist's work and then progressively go back in time. Still, even if the user has a plan in mind, it appears hard to stay on the right track. As Foss states when she refers to the 'embedded digression problem' (p. 2), "lots of interesting neighboring information is around to distract you from the main task". But, as she states, "pursuing multiple paths and digressions leads to much trouble: (...), forgetting to return from digressions, and neglecting to pursue digressions you intended to follow". Distraction readily leads to disorientation. According to Conklin (1987) disorientation is a second problem that is endemic to the use of hypertext. A disoriented learner has no idea how the current topic relates to the rest of the material and in consequence may have no idea of how to proceed.

Distraction and disorientation gets in the way when it comes to fruitful learning. As Kibby (1989) puts it (p. 127): "in several cases it seems clear that the subjects are quite absorbed in the task (...) and as a result fail to learn adequately".

What makes learning in hypertext so demanding? Whereas most learners nowadays do have tremendous experience with linear text, they are relatively inexperienced with respect to learning with hypertext. Compared to hypertext, linear text takes much regulation out of the hands of the learner. Linear instructional text is generally highly preorganized for learning. The learner does not have to decide on the order in which to learn the topics, and usually overviews are provided in the form of 'advance organizers' (Ausubel, 1963) and summaries. In hypertext, or more generally, unstructured exploratory environments, regulative activities such as planning are left to the student. It must be doubted whether students are capable of performing all regulatory actions on their own. They might just not have acquired the 'literacy' to handle the exploratory environment (cf., Marchionni, 1988).

Analogous to problems with exploration in hypertext, experiences in a simulation context reveal inadequate exploration as well. Goodyear et al. (1991) and van Joolingen (1993) list a large number of studies that reported problems with exploratory and discovery learning in simulation-based learning environments. These problems manifest themselves in not being able to state hypotheses, to design experiments, to systematically test hypotheses, or to draw correct conclusion from the outcomes of experiments. In analogy with the learner's behavior in hypertext, one observation is particularly relevant. De Jong (1991) remarks (p. 221) that "learners may easily get involved in making changes randomly instead of purposefully manipulating variables and parameter values". Goodyear et al. labeled this unstructured, undirected way of interaction as 'floundering'. Floundering might be highly analogical to the behavior of the disoriented learner that browses aimlessly through a hypertext environment.

Active engagement alone is not sufficient. As Mayes et al. (1990) reminds us: "Active exploration of a hyperspace is by no means the same thing as active exploration at the conceptual level". Exploration is more than actively clicking buttons. For it to be effective, exploration should be a methodic, goal directed activity.

## 1.2 Support for information space exploration

Similar problems seem to occur during learning with simulations and hypermedia. Highly similar explanations for the underlying causes are given. With respect to learning with hypertext, Conklin states (p. 40) "a fundamental problem with using hypertext is that it is difficult to become accustomed to the additional mental overhead required". De Jong's (1991) statement (p. 277) is comparable; "learning by means of simulations puts a high cognitive demand on the learner".

Some have suggested that cognitive overload is a crucial factor in explaining ineffective patterns of learning or problem solving (see e.g. Sweller, 1988; Jansweijer *et al.*, 1990; Paas, 1993). Others have indicated that lack of a well organized knowledge base prevents proficient employment of self regulatory actions (Veenman, 1993; Alexander *et al.*, 1994; Kamsteeg, 1994). Kamsteeg argues (p. 40), for example, that "some a priori knowledge of the domain appears necessary to decide what is necessary to explore." Alexander et al. (1994) claim (p. 215) that with an initial lack of prior knowledge, learners "remain unable to tackle the increasingly more demanding exposition presented to them and continue to loose ground".

The literature is inconclusive on the exact causes of insufficient regulation. Exploration does require the student to perform complex cognitive actions such as planning and monitoring, and it is likely that the observed ineffectiveness of learning in exploratory environments arises from an inability to meet the cognitive demands made by the environment. Learner activity is assumed desirable, but in plain exploratory environments covering unfamiliar material, too much is left to the student.

The mission of the work documented in this thesis was to design support that takes over part of the regulation in exploration. In this, we have concentrated the effort on a single regulatory activity that could be found both in hypertext and simulation-based exploratory learning,[2] namely that of 'information space exploration'. In the following paragraphs this and various other central notions will be elaborated.

In this thesis, *exploration* is defined as the self regulation of learning. Following Kamsteeg (1994), a distinction is made between exploration and discovery. Discovery learning is seen as actively constructing knowledge, whereas exploratory learning is perceived as actively regulating learning. In a free exploratory environment, knowledge is not necessarily discovered, it may all be given. What is given, however, lacks the instructional design structure inherent to expository material. In the extreme case, no goals are given, no sequence is imposed upon the material, no assignments, summaries etc. are given and no means are provided to evaluate whether the goals are reached.

[2]See (Njoo, 1994) for an overview of exploratory- and discovery learning processes in simulation-based learning.

In exploration, learners have to regulate their own learning. One of the aspects to be regulated is the deciding upon the order in which to explore the subject matter elements. In this work this activity is named *'information space exploration'*.

Information space exploration is to cover both the process of deciding in what order to explore the relations between variables in a simulation model and the topics in a hypertext. In the hypertext field, the latter is better known as *'navigation'*. Both a simulation model and a hypertext database can be perceived as information spaces, hence the term 'information space exploration' will be used hereafter.

As claimed above, learners may lack both regulatory capacities and domain knowledge to beneficially regulate their own learning. With respect to information space exploration, they may fail to decide upon a beneficial order in which to explore information space elements. They may end up going from complex to simple, pursue paths that lead them to conceptually unrelated topics, or try to learn tasks of which they have not mastered prerequisites.

The mission of this work is to provide learners with means that could make them regulate information space exploration in a beneficial way. In this, it is perceived crucial to try to retain the potentially beneficial aspects of exploration. That is, we did not aim at providing learners with fully directive guidance that would make them follow the one and only optimal sequence through information space. We aimed at means that would allow learners to decide upon a sequence that would be beneficial to them, given their prior knowledge and learning style. Finally, means for support would address mainly the acquisition of knowledge rather than the acquisition of skills.

## 1.3 The issues

In summary, the main question in this work was:

- **How can an environment be designed so that it supports learners to perform information space exploration in a beneficial way.**

This question could not be answered without knowing what aspects make information space exploration beneficial, hence a first question to be answered was:

- **What are the things that matter for information space exploration to be beneficial?**

## 1.4 Context

The work reported here was performed in the context of two different projects. The first was the MIOS[3] project. MIOS stands for 'Methodologie voor Intelligente OnderwijsSystemen', that is, 'Methodology for Intelligent Teaching Systems'. The MIOS project aimed at providing authors of learning environments with both technical and conceptual support for the development of such environments. Most of the theoretical work and the work on support for exploration in hypertext, as reflected in the chapters 2 up to and including 6, was done within the context of this project.

[3]The MIOS project was funded by the 'Profileringsfonds' of the University of Amsterdam.

Where MIOS aimed at learning environments in general, a second project, SMISLE (System for Multimedia Integrated Simulation Learning Environments), was more narrow in scope. SMISLE[4] addressed the development of environments for simulation-based learning.

The SMISLE project resulted in a well tested authoring environment (see de Jong & van Joolingen, 1995; King *et al.*, 1995). This environment provides tools for the construction of simulation models as well as for the creation of 'measures' for instructional support. The work reported in the chapters 7 up to and including 9 addressed technical and conceptual support for one of the measures in the SMISLE, that of 'model progression'.

## 1.5 Outlook

This thesis consists of four parts. **Part A** contains a literature review dedicated to the question of things that matter in information space exploration. **Part B** and **C** document two exercises in design, implementation, and evaluation of environments dedicated to the support of exploratory learning. The final **part D** provides a reflection on experiences from both exercises.

In the following paragraphs, we will outline the contents of each chapter. An overview of the chapters and the connections between them can be found in Figure 1.1. In the paragraphs below, terms printed in *italic* refer to elements in this figure.

In the present chapter we sketched a problem of *ineffective exploration*. The intention of the study documented in this thesis was to come up with support for one aspect of exploration, that of information space exploration. In **chapter 2**, based on a review of empirical studies in the field of subject matter sequencing, *requirements* for support are outlined. In short, for information space exploration to be beneficial, the exploratory sequence should:

- establish a *connection to prior knowledge*.
- reflect essential domain and learning-related aspects of the subject matter. This requirement was labeled *tailored rationales*. A related requirement stated that sequence should be closely related to the structure that acts as rationale, be structure-related.

Finally, to allow learners to adjust exploratory sequence to their individual needs, any support provided should be:

- *non-directive*, thus facilitate rather than guide.

*Solutions* for support were sought in existing instructional design (ID) theories (**chapter 3**). A conclusion from a review of the ID theories was that the model progression approach, as originally presented by White and Frederiksen, satisfied most requirements. The scope of this approach is, however, limited to causal domains only. For use within the context of simulation-based learning, the subject of the SMISLE project, this restriction was not problematic. One of the exercises described in this thesis would thus be dedicated to an operationalization, implementation, and evaluation of the model progression approach.

In the context of the MIOS project, however, a more generally applicable approach was sought for application to hypertext-based learning. In this context, it was decided to design support by

[4]The SMISLE project was an EC funded cooperation in the DELTA stream. Partners in SMISLE were the universities of Twente and Amsterdam and the industrial partners Marconi Simulation, Framentec, and ESI. Test sites in SMISLE were IPN-Kiel and the university of Murcia

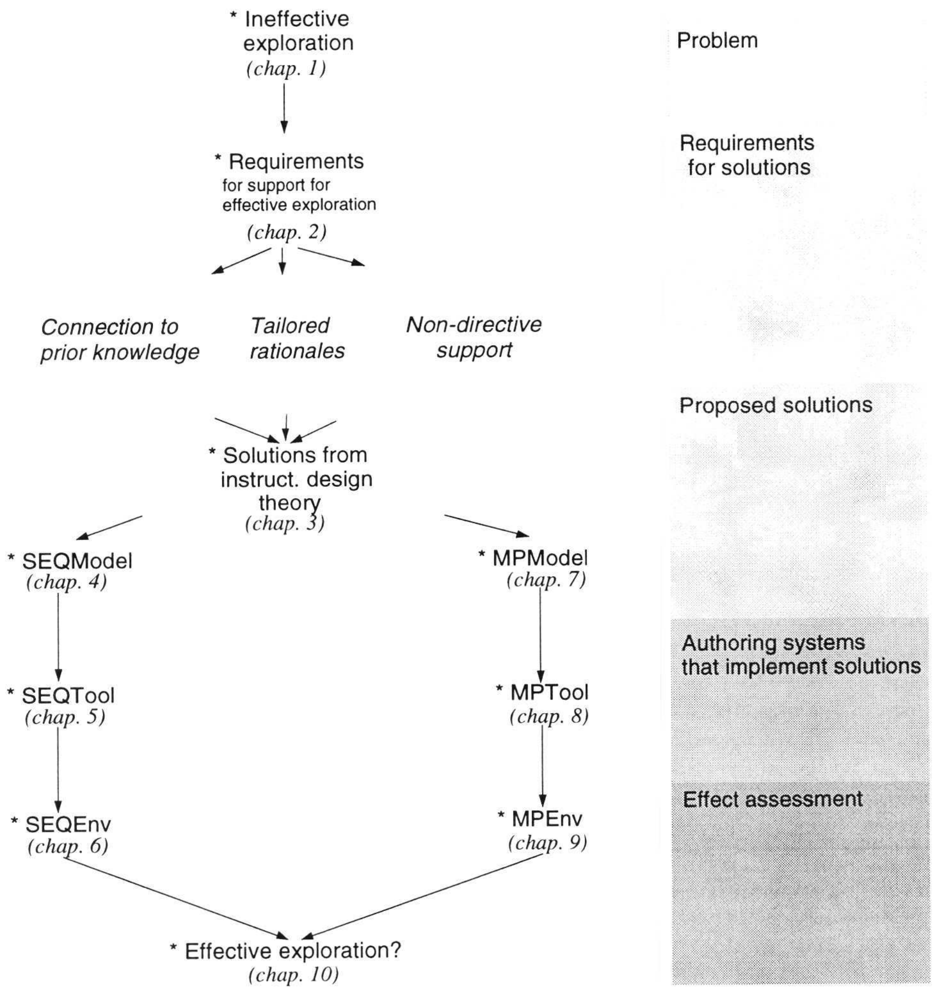



Figure 1.1: An overview of the contents of this thesis

integrating elements from currently available prescriptive theory. A majority of the prescriptive theories in the review of **chapter 3** apparently focused at establishing a *connection to prior knowledge*. An integration of ideas from several theories resulted in generally applicable solutions for support for connection to prior knowledge. On the other hand, the theories failed to provide such solutions for support that could meet the requirements of tailored rationales and non-directiveness. With this conclusion, Part A ends.

**Part B** describes the exercise that was dedicated to the design, implementation and evaluation of support for information space exploration in a hypertext context. **Chapter 4** is dedicated to finding solutions for the remaining requirements, that of tailored rationales, structure-relatedness and non-directive support. The requirement of *tailored rationales* was tackled by means of analysis of expert subject matter sequencing. In this analysis, from a highly diverse collection of written instructional material, domain structures were reconstructed. This reconstruction allowed to interpret the subject matter sequence in terms of underlying rationales. Analysis of a variety of sequences lead to statements on the nature of expert subject matter sequencing. These statements were the basis for a prescriptive model (*SEQModel*) for so-called 'structure-related' sequencing. Support based on this model was thought to satisfy the requirement of *tailored rationales* and *structure-relatedness*.

The model for structure-related exploration was a basis for an authoring tool (*SEQTool*). The design and implementation of this tool is described in **chapter 5**. The intention of SEQTool was to support the creation of graphical overviews of subject matter. In the construction of these overviews, *SEQTool* makes deliberate use of conventions in reading direction to provide *non-directive support* for learners to explore in a structure-related manner. The effects of the aforementioned support were assessed by means of an experiment that compared environments with and without a graphical overview generated by SEQTool (**chapter 6**). With chapter 6, Part B of this thesis ends.

**Part C** describes a second exercise, an operationalization, implementation, and evaluation of the Model Progression approach. **Chapter 7** is dedicated to the operationalization of the approach. A first task was to gain insight into the applicability of the approach outside the scope of the domain of illustration in which terms the approach was originally described. To this end, a new domain was analyzed with the question in mind whether the model progression approach could readily be applied. This endeavor, together with a review of related work, lead to a more general description of model progression. A more operational definition (*MPModel*) was obtained by creating a vocabulary of terms for modeling within the SMISLE and subsequentially expressing the prescriptions of MPModel in terms of this vocabulary.

**Chapter 8** describes the implementation of MPModel in an authoring tool (*MPTool*), followed by an evaluation of this tool. The validity of operationalization, the feasibility of implementation and MPTool's efficacy of support were evaluated by an analysis of experienced and inexperienced authors constructing model progression with and without MPTool.

Following an evaluation from the author's perspective, **chapter 9** describes an evaluation from the learner's perspective. In an experimental setting, learners worked with two versions of the same simulation. One version presented the domain of oscillation by means of a simple-to-complex sequence of models (*MPEnv*), the second version provided the most complex model only.

Part B and C covered two exercises in non-directive support for exploratory learning. Two different forms of support were applied within two different contexts. The question is, have we managed to come up with adequate forms of support, support that helped rather than guided learners to perform information space exploration in a for them beneficial way? To answer this question, **chapter 10**, or **part D**, provides a reflection on the results of both exercises.

# Part A

# Requirements for support 2

## 2.1 Introduction

In this chapter an attempt is made to answer the question of what makes information space exploration beneficial. To come to an understanding of the things that matter in information space exploration, empirical studies in the discipline of subject matter sequencing[1] were reviewed. This discipline is traditionally concerned with the question as to whether the order in which subject matter elements are learned affects learning outcomes. Insights obtained from the literature in subject matter sequencing are thus assumed to be relevant for information space exploration, as this activity was defined as *the deciding upon the order in which to explore subject matter elements* (see section 1.2).

The decision to work toward support for enhancement of information space exploration was inspired by the assumption that the exploratory trajectory affects learning. Oddly enough, little is known about the relation between the exploratory trajectory and the knowledge obtained. In contrast, the relation between subject matter sequence and knowledge acquisition has been studied heavily, resulting in an insight into the question whether sequence affects acquisition and thus whether the assumption is valid.

**Does sequence make a difference?** Does sequence affect acquisition? In trying to answer what aspects make a difference for a sequence to be beneficial, this has been a first question to ask. Subject matter sequence has long been assumed to be an important variable in instruction. Many in the field claimed that the sequence of presentation of knowledge elements matters. Ausubel (1963) even contended (p. 213) that "all of the possible conditions that affect cognitive structure it is self evident that none can be more significant than the internal logic and organization of material". Only in the sixties, sequence got investigated in a systematical manner and on a large scale. The introduction of programmed instruction in those days was accompanied by a recognition of the necessity of operational definitions of 'logical' sequence. This recognition triggered a vast amount of so called 'scramble' studies. These were studies that compared the effects of a 'logical', usually teacher constructed, sequence with those of a scrambled one, a sequence in which topics were presented in random order.

Unexpectedly, many of those 'scramble' studies failed to reveal effects of a carefully organized presentation. Vlachouli-Roe et al. (1962), for instance, assessed the effects of scrambling programmed instruction in elementary probability for college freshmen. This study certainly provided no evidence that scrambling impaired retention. To find out whether scrambling would affect re-

[1] 'Sequence' is defined here as the ordering in time of a series of knowledge elements, where the ordering is based on certain 'rationales' (Lodewijks, 1983). 'Rationale' is defined as an 'ordering structure', that structure which is selected to act as basis for the sequence. For instance, in a chronological sequence, temporal structure is used as rationale. That is, the sequence is based on a temporal structure.

tention and transfer in less mature students, Levin and Baker (1963) undertook a similar scrambling study, now with second graders. The domain of study was elementary geometry covering notions such as points, lines, and angles. This study too revealed no differences on tests for acquisition, retention, and transfer.

As these studies were so unsupportive of pedagogical intuition, many have tried to find methodological or technical shortcomings. Lodewijks (1983), for instance, hypothesized that rationale-based sequence might have had effects on the cognitive structure that could not be detected by standard achievement tests. However, even with tests that were specifically designed to unravel resulting cognitive structure, Lodewijk's scramble study did not reveal any differences.

In some studies the observed lack of effect may have been be due to methodological and technical shortcomings, but too many studies failed to reveal effects of sequence. Tobias (1973), for instance, reviewed 11 scramble studies and reports effects in only two of them. With some overlap with the studies reviewed by Tobias, Mayer (1977) also reviewed 11 studies and reports performance differences in three. Thus, the results are at least inconsistent and the idea that 'sequence affects acquisition and retention' was not supported by the data. With that, the initial assumption on the relation between exploratory trajectory and learning received little support.

**Explanations for counterintuitive findings** Scrambled sequence does not necessarily deteriorate performance. Several researchers searched for explanations for this counterintuitive finding and came up with various hypotheses on aspects that might have obscured interpretations.

A first explanation referred to depth of processing. As the implicit structure needed to be discovered, learners in the scramble conditions might be have been forced to self-impose structure upon the material. As a result, the processing may have been deeper in the scrambled sequences than in the logical ones (cf., Lodewijks, 1983, p. 98). Deeper processing is assumed to promote better retention. As such, the extra effort demanded to infer structure may have compensated for the lack of initial organization.

A second type of explanation focused on aptitude-treatment-interactions (ATIs). High ability students might have been activated particularly by the scrambled sequences to self-impose structure on the material. Or, for those students familiar with the material, a super-imposed logical sequence might have interfered with the student's habitual way of information processing. Indeed, several studies revealed that, for instance, with learners with low prior knowledge or low abilities, logical sequence can positively affect learning (see section 2.3). ATIs should thus be considered relevant in explaining effects of sequence.

A third type of explanation addressed the nature of the so-called 'logical' sequences. Other and maybe better logical sequences might have lead to different results. Several researchers voiced a dissatisfaction with respect to the nature of the logical sequences used in the scramble studies (see e.g., Coleman-Stolurow, 1975; Lodewijks, 1983). The critique was that most of the logical sequences were constructed quite arbitrarily and consequently lacked a well defined rationale. Lack of well defined rationales hindered replication studies as well as prevented from making a principled distinction between those sequences that were found beneficial and those that were not. In reaction to the critique, several attempts were made to describe the nature of sequences. Section 2.2 documents those attempts. Following this, we will try to make some statements on aspects that determine the quality of a sequence.

The benefits of a particular sequence can not be studied apart from aspects in the target population, such as prior knowledge and learning style. In the field of subject matter sequencing, a large part of the experimental work is dedicated to the study of the influence of prior knowledge, intelligence, field dependence, etcetera. Such studies reveal that aspects in the learner determine the benefits of sequence to a large extent. Thus, when designing for beneficial exploration, individual differences should be an important consideration. In section 2.3, aspects in the learner that influence the effects of support for sequence are discussed.

In summary, the intention of the analysis of empirical work on subject matter sequencing is to take a first step toward a prescriptive model for support for information space exploration. By tackling the above mentioned questions, we expected to gain insight into the things that matter in sequencing.

## 2.2 Aspects in the sequence

The scramble studies compared 'logical' sequences with scrambled ones, the question was, what makes a sequence a logical one? Many of these so-called logical sequences were sequences constructed by experienced teachers. Such teacher-constructed sequences were named 'communal' sequences. For investigating the question as to whether sequence can affect learning, these communal sequences might have been useful. However, for gaining grip on the aspects that make a sequence a beneficial one, communal sequences were generally insufficiently described (Coleman-Stolurow, 1975). To study the nature of beneficial sequence, sequence must be defined so that the definition allows for replication, and after a period of scramble studies, the necessity of operational definitions for the various rationales of logical sequences was evident (Coleman-Stolurow, 1975; Eylon & Reif, 1984).

**Logical sequence** For given subject matter material, various 'logical' sequences may be constructed. A comparison of any logical sequence with a scrambled one might demonstrate the relative effectiveness of that particular logical ordering. Such a comparison would, however, not yield insight into the effectiveness of any other sequence upon the same material that could be considered to be logical too. Some in itself logical orderings are found to be inferior to alternative logical orderings upon the same material. For instance, studies investigating deductive versus inductive sequences (see e.g. Evans *et al.*, 1962; Koran *et al.*, 1976) have revealed such differential effect. Lodewijks (1983) reviewed numerous studies on inductive versus deductive sequences and reports (p. 59, translated from Dutch) substantial differences. "If the inductive variant benefited anyone, it was only the student with high ability. The deductive variant is more likely to lead to beneficial results, irrespective of intellectual ability of the student." Hence, different logical sequences imposed upon the same material may have different effects on learning.

**Rationales** First, rationales used to create logical sequences were to be clearly defined. Posner and Strike (1976) were among the first to systematically investigate in what ways content can be sequenced. Analysis of expert sequencing in combination with available prescriptive theory has been the source of their categorization of 'rationales'. 'Rationales' were previously defined as 'ordering structures'. An ordering structure is that structure that is selected to act as a basis for the sequence. For instance, inductive and deductive sequences are inextricably bound up with hierarchical ordering structure. A deductive sequence 'traverses' a hierarchical structure from class to instance, an inductive sequence from instance to class. In both cases hierarchical structure 'acts as rationale'.

One might see the categorization by Posner and Strike as an ontology of relations that are found to act as rationale. The rationales are defined in terms of two types of 'empirical properties'. The first type refers to empirical properties of a given *subject matter*, a second to empirical properties of the *learning process*. Empirical properties of the given subject matter are, for instance, indicated by *temporal*, *spatial*, *causal*, but also *hierarchical* relations among entities in domains. Examples of sequences based on such rationales are: The history course taught chronologically, based on a temporal rationale; The curriculum on the periodical system of elements that is organized starting with elements with a low atomic number to elements with a high atomic number, based on an empirical complexity rationale; The geography course that starts at the student's native country and that gradually introduces more and more remote countries, based on a topological rationale; The course on a taxonomy of plants that starts with explaining the main classes of lower and higher plants and ends with discussing the characteristics of particular species, based on a hierarchical rationale.

Empirical properties of the learning process refer, for instance, to *familiarity*, *difficulty*, and *empirical prerequisite* relations. An example of a sequence based on a so called 'learning-related' rationale is the course on oscillatory motion that starts with free harmonic oscillation, then introduces oscillatory motion with friction and ends with this motion driven by an external force. Here the sequence is based on a 'difficulty-related', also simple-complex, rationale.

In chapter 4 the categorization of rationales is discussed more elaborately. The same chapter also provides a graphical overview of the main categories of rationales (section 4.3).

### 2.2.1 Tailored rationales

The introduction of the notion of *rationale* gave rise to studies that compared effects of sequences of similar subject matter based on different rationales. Eylon and Reif (1984) compared sequences based on either a hierarchical rationale or temporal rationale. The domain of this study was (p. 25) "a fictuous universe of particles" where the instruction aimed at an understanding of physics laws in the domain of mechanics. The subjects were high school students of advanced physics. Tests for knowledge of hierarchical structure and temporal structure revealed an interaction effect of rationale choice and knowledge of structure acquired. For both conditions, knowledge of the structure that acted as rationale was recalled better. Evidently, rationale choice influenced acquisition of knowledge of structure. Almost similar results were reported by Kulhavy, Schmid, and Walker (1977). Kulhavy et al. compared three sequences; one based on a hierarchical rationale, one based on a temporal rationale, and a scrambled sequence. With respect to overall results, the scrambled sequence was found detrimental compared to the rationale-based sequences. For recall of temporal structure no differences were found between temporal and hierarchical organization, however, for recall of hierarchical structure, the group with a hierarchical rationale-based sequence performed significantly better. Remarkably, for the recall of hierarchical structure no differences were found between a temporal rationale-based sequence and the scrambled sequence.

The studies by Eylon and Reif, and Kulhavy, Schmid, and Walker suggest that acquisition of knowledge of structure may in some cases be enhanced by having the sequence relate to the 'target' structure. Target structure is that structure of which an understanding is defined as learning goal. Other work indirectly confirms this statement. A study by Edwards and Hardman (1988), for instance, showed that students following hierarchy-based sequences through a hypertext were significantly better able to reproduce the hierarchical structure of the domain than a group that followed a less 'structure-related' sequence. It should be noted that this latter sequence was certainly not a scrambled one. In both conditions, students were autonomous in their decision upon the order in which to explore the hypertext.

Sequencing material consistent with a target structure seems to be important in conveying that structure. For the design of support, this observation may have implications. As Posner and Strike put it (p. 666), *"sequence should be logically consistent with the structure of the subject matter material"*. That is, if a learning task demands an understanding of a topological structure, that topological structure should, if possible, act as rationale.

With this, we have got to a first requirement on the nature of prescriptions for support. As rationale choice may affect the acquisition of knowledge of structure, rationale choice should be tailored to the target structure. If a learning goal is to understand hierarchical structure, then hierarchical structure should act as rationale, if a learning goal is to understand temporal structure, temporal structure should act as rationale. Hence, we formulate the requirement of *tailored rationales*. This requirement says that rationale choice must be tailored to the target structure.

Some words have to be addressed to a special kind of structure, that of so called *learning-related structure* (see Posner & Strike, 1976). This is structure that, for instance, reflects prerequisite relations, or differences in difficulty, familiarity among the composing entities. Posner and Strike have argued that these learning-related structures are as important as are the so called domain-related structures to act as rationale for sequencing. Therefore, if such learning-related aspects of structure are known, rationale choice should be tailored to such learning-related structures as well. Hence, we will extend the requirement of tailored rationales to include tailoring rationale choice to learning-related aspects of structures.

- **Tailored rationales:** *rationale choice must be tailored to the target structure or to learning-related aspects of the target structure.*

In the following paragraphs, we will elaborate on issues that play a role in the author's decision on rationale choice. Here we will try to be more explicit on things that matter when deciding upon rationales.

**Issues in tailored rationales** The requirement of tailored rationales implies that rationale choice should be specific to the nature of the domain or to learning-related aspects of that domain. For automized support, this statement should be operationalized by making explicit *when to choose which rationale*. The categorization scheme of rationales as that provided by Posner and Strike is not much of a help in deciding on rationale selection as it lacks such guidelines.

In a prescriptive theory that adheres to the requirement of tailored rationales, statements should be made on when to use which rationale. Such statements were sought in currently available prescriptive theory (as documented in chapter 3). Some of the instructional design theories discussed in the following chapter prescribe the use of a single rationale type for all sequencing. Gagné, for instance, prescribes that all content should be organized on the basis of a single prerequisite rationale. Ausubel does the same for a hierarchical rationale. However, those that have studied expert teacher sequences (see e.g., Lodewijks, 1983; Posner & Strike, 1976; Slavenburg, 1977) claim that it is usually not desirable to adopt such a single rationale approach. One rationale for all kinds of domain structures can do no justice to the very nature of various domain structures.

Then, a statement would be to say that if one of the structures as listed by Posner and Strike could be detected in the target domain, this structure should act as a rationale. A complication, however, is that subject matter is usually not onedimensional. More than one potential ordering structure might be present in the material. Hence, if this is the case, one might either select the most important ordering structure or try to combine several ordering structures.

**Categorical dominance** The selection of a 'most important' ordering structure might be based on an understanding of the relative importance of the rationales. This touches upon the issue of so-called 'categorical dominance'. Categorical dominance refers to the relative importance of rationales. That is, if more than one rationale can be applied, some rationales might take precedence over others. Posner and Strike mention the example of the three rationales 'empirical prerequisite', 'difficulty', 'interest', where 'empirical prerequisites' is judged to be most important and is, therefore, defined to take precedence over 'difficulty' and 'interest' respectively.

**Combining rationales** To deal with multidimensional structure, one might try to combine sequences based on more than one ordering structure. The work of Sasson (1971) yields some evidence that an approach that combines rationales can be beneficial over a single rationale approach. In Sasson's work, a combination of a hierarchical and temporal rationale-based organization was found to be superior compared to organizations based on either a temporal or hierarchical rationale. Sasson's recall task was non-specific, it tested knowledge for all types of knowledge present in the domain.

In addition, in expert teacher sequencing, sequences based on rationale combinations are found more frequently than single rationale-based ones. Chapter 4, for instance, documents many of such rationale combinations. According to Posner and Strike, highly sophisticated sequences often employ more than one rationale. Lodewijks (1983) and Slavenburg (1977) argue that different rationales are to be combined to construct sequences that both deal with the properties of the domain and with learning-related aspects of that domain.

A next question is how various rationale-based sequences can and should be combined. The next example shows that different rationales might be applied at different levels of granularity in curriculum construction. Reigeluth's Elaboration theory, for instance, prescribes to apply a hierarchical rationale to create an overall (coarse-grained) curriculum and to apply a prerequisite-first rationale within levels of the hierarchical structure. Several examples of such differences between coarse- and fine-grained organization are found in expert sequencing (see chapter 4).

It was argued above that it does matter which rationale is used to create an overall organization. When constructing a framework for support for sequencing, one should be sensitive to the idea that some rationales may apply to certain levels of curriculum construction only and that categorical dominance might vary among different levels of curriculum construction. In chapter 4 we will come back to this issue and describe how experienced authors handle different levels of curriculum construction.

### 2.2.2 Structure-relatedness

Rationale selection is a first step in deciding on sequence. When creating a sequence, it is not sufficient to just select a structure to act as rationale. For instance, a simple non-branched structure can be traversed in various manners. One may traverse in a connective manner and thus start at one of the outer entities and traverse from there in a forward or backward manner. In contrast, one may start somewhere in the middle of the structure and work outwards, or just 'jump' through the structure. Figure 2.1 shows several of such traversal routes along a simple non-branched structure.

Since several options for traversal are open, statements must be made on the nature of beneficial traversal.

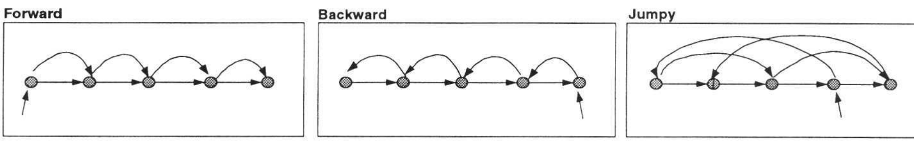



Figure 2.1: Three examples of traversal routes along an identical structure

Studies by Eylon and Reif (1984) and Kulhavy et al. (1977) suggest that, to obtain positive effects, sequence should be closely related to the ordering structure. In the experiment of Kulhavy, Schmid, and Walker rationale-based sequences are found to be closely connected to the structure that acts as rationale. That is, the structures are traversed in a connective manner. The sequence, for instance, based upon a temporal rationale, starts at the event most remote in time and chronologically each subsequent event is presented to the student. Thus, in presenting the composing elements, the structure is traversed in a highly 'structure-related' manner. The 'jumpy' traversal pattern in Figure 2.1 would not readily be found.

Eylon and Reif (p. 27) contend that sequence that is a systematic traversal of structure "will help to explicate that structure". Lodewijks voiced the expected benefits of structure-related sequence; such sequence should more readily allow the reconstruction of domain structure. In sequences that were observed to positively affect acquisition of structure, not only the rationale choice is tailored to the specific task, but the resulting sequence is also closely related to the structure that acts as rationale.

To summarize, in beneficial sequence, two aspects appear to be of importance: *tailored rationales* and *structure-relatedness*. Thus, a second requirement is that of:

- **Structure-relatedness:** *sequence should be closely related to the structure that acts as rationale.*

**Issues in structure-relatedness** The requirement of structure-relatedness implies that sequence should be closely related to the ordering structure. Posner and Strike do not go any further than listing ordering structures. They indicate, for instance, that topological structure has acted as a basis for decisions regarding the sequence. This was where their categorization scheme ends, it does not give any indication as to the nature of the sequence to be imposed upon such topological structure.

Using the example of topological structure, many different topology[2] based sequences are possible. For instance, close-to-far, far-to-close, right-to-left, left-to-right, top-to-bottom, bottom-to-top, west-to-east, etc. All these sequences can be considered to be closely related to the ordering structure, hence satisfy the requirement of structure-relatedness. Yet, it should be noted that some of these rationale-based orderings can be observed far more frequently than their counterparts. For instance, close-to-far, left-to-right sequences are common, where far-to-close and right-to-left sequences are rarely found (see e.g., Levelt, 1989; Winn, 1983).

[2]Indeed, no definition of a topological structure is given. As for now we assume topological relations to incorporate a wide range of links indicating spatial organization.

Certain directions are strongly prefered over others, as is the left-to-right direction over the right-to-left one[3] (see Zwaan, 1965). Notably, conventions exist with regard to 'direction' of a sequence imposed upon a certain type of structure. Levelt labeled these as conventions of 'natural order'. We prefer the term 'direction' over 'order' to indicate that direction is just one aspect of sequence or order.

The question is whether it matters for learning to follow such natural direction. If it does, it might be valuable to extend the categorization scheme with, for each rationale, indications of natural direction. In chapter 4, a first step is made to get to such an extension.

A dissatisfaction with the insufficient definition of the 'logical' sequences as used in the scramble studies has lead to this section on aspects in the sequence that may affect learning. Equally important are aspects in the learner. In the following sections we will discuss studies that reveal how effects of sequence could be affected by aspects in the learner.

## 2.3 Aspects in the learner

### 2.3.1 Prior knowledge

One of the most important factors affecting the effects of sequence is prior knowledge. The crucial role of prior knowledge is well put in the motto of the dissertation of Lodewijks, being a quote of Ausubel et al. (1978), "If I had to reduce all of educational psychology to just one principle, I would say this: The most important single factor is what the learner already knows. Ascertain this and teach him accordingly". It is difficult to over estimate the influence of prior knowledge on learning (cf., Alexander *et al.*, 1994). Evidence for the influence of prior knowledge was, amongst others, provided by Tobias (1973) who showed that with little prior knowledge, negative effects of scrambling could be substantial. Tobias provided subjects with a scrambled and a rationale-based ordering of a popular and a technical passage on heart disease. Scrambling lead to inferior performance for the unfamiliar technical text only. While working with the familiar popular material, the subjects in the scramble condition acted much as if the material had been logically sequenced. The scrambled condition with the unfamiliar material revealed completely different behavior. The behavior could best be described as revealing "confusion and consternation" (Tobias, 1973, p. 139). Consequently, the subjects expressed a great need for support. They frequently asked for instruction, or wondered whether instructions had been accidentally omitted. In a follow-up study, Dyer and Kulhavy (1974) successfully replicated the study and found similar results

Familiarity, and thus prior knowledge, is an important factor in the effectiveness of sequencing measures. This is underlined when considering a study by Natkin and Moore (1977). This study used nonsense and thus completely unfamiliar material. Natkin and Moore provided a sequence of so-called 'interlocking' definitions, where each new notion is explained in terms of a previously presented notion. An example of such interlocking definitions from the material of Natkin and Moore is "FAV means house, LOQ means green FAV, PUL means large LOQ". With such material, scrambling substantially deteriorated posttest performance. Mayer (1977) interpreted these results in terms of his 'assimilation to schema' theory. This theory says that if relevant schemata are available, new material can be connected to previously acquired knowledge. If no such schemata

[3]It should be noted that left-to-right direction preference is not universal. It is a learned convention that is obtained with the acquisition of literacy (Tversky *et al.*, 1991). In cultures that have written language that reads from right-to-left, a reverse order tendency is found (also Tversky and Kugelmass).

are available, new knowledge remains isolated. Where no relevant schemata are active, a well designed sequence may help to provide anchoring points. Referring to the example material of Natkin and Moore, the sentence "LOQ means green FAV" is meaningless if one has not learned before that "FAV means house". With the reference to 'house', an anchoring point is provided, thus a meaningful connection to otherwise meaningless material.

On the other hand, when relevant prior knowledge is available, sequence appears to be less crucial. An experiment by Tillema (1983) showed, for example, that familiarity largely reduced the differential effects of different sequences, in this case Web[4] versus linear sequences. As Tobias showed before, with familiar material, sequence does not really matter. Tobias suggested that with familiar material, students already possess a general outline of the subject matter in which to fit new information, irrespective of the order in which this information is presented. A study by Kintsch, Mandel, and Kozminsky (1977) supported this, as the subjects in this study managed to successfully reconstruct scrambled stories on the basis of their knowledge of story schemata. Elements presented out of order could still be connected to prior knowledge.

In the first section of this chapter we have pointed at inconsistencies in the outcomes of empirical studies in sequencing. In this section we have tried to motivate that differences in prior knowledge of subjects may be an important factor explaining inconsistent results. According to Mayer's assimilation to schema hypothesis, with familiar material, a scrambled and rationale-based sequence may yield similar results. However, as Mayer contended, if the material is unfamiliar, well designed sequence may be crucial.

### 2.3.2 Idiosyncrasy in prior knowledge structure

#### 2.3.2.1 Interference

As claimed in the previous section, well designed sequence is thought to be necessary for the acquisition of unfamiliar material. In this section, we will argue that, with familiar material, superimposed sequence may even interfere with the knowledge acquisition process of the individual learner (Mayer, 1977). Where learners expect to be able to assimilate new knowledge into currently available schemata, incongruent material demands 'accommodation', or restructuring of those schemata (see Rumelhart & Norman, 1978).

Sometimes restructuring may be necessary if current schemata are insufficient. But, if current schemata suit the task, the designer of sequence has a task to try to make the organization of the material suit the schemata. Both Ausubel (1978) and Bruner (1966) have postulated that an optimal processing of subject matter is only possible if this subject matter is structurally congruent with the way the learner habitually processes material, or has already organized that material into cognitive structures. This assertion is supported by a finding of Mayer (1978) who compared the effect of logical and scrambled sequences that were accompanied by advance organizers. Here, the scrambled sequence with organizer did better than the one without, whereas for the logical sequence the reverse was the case. Surprisingly, a logical sequence with advance organizer lead to detrimental results compared to the logical sequence that lacked the advance organizer. Mayer's explanation for this latter effect was that the 'logical sequence' may have interfered with learners' knowledge structure previously created on the basis of the organizer.

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[4] Web-teaching is a form of sequencing where the curriculum iteratively elaborates on a few central notions in the domain. Web teaching is highly similar to Ausubel's notion of progressive differentiation (see section 3.2.1).

Assuming that the learner's cognitive structure has idiosyncratic characteristics, in familiar and not too complex domains a single 'logical' sequence may not be the best for all learners.

#### 2.3.2.2 Autonomy

A question is then whether learners are capable of organizing material so that it suits their needs. The work by Zimmer (1976) and Moore, Hauck, and Furman (1975) revealed that the knowledge acquisition process can greatly be enhanced when the learner is allowed to self-impose structure upon the subject matter. Moore et al., for instance, had subjects learn 25 common words. In the self-imposed condition learners were allowed to cluster the words into 7 or less categories. The group in the super-imposed condition received a clustered set of words. The results of a recall test revealed superiority of the self-imposed organization.

With respect to sequence, a similar observation can be made. Three studies (Flammer *et al.*, 1976; Lodewijks, 1983; Seidel *et al.*, 1978) that compared self-imposed with super-imposed sequence all revealed superiority of self-imposed sequence. Flammer, Buchel and Gutmann found retention benefits of self-imposed sequence for material on prose learning. Transfer gains were expected but not found. This study was done with college students. Lodewijks compared two super-imposed sequences (a logical and a scrambled one) with a self-imposed one, while working with 2nd grade high-school students in the domain of physics. In this study he found both acquisition and retention benefits of the self-imposed sequence. A replication, by the same author, in a different context yielded similar findings. Another indication that autonomy in sequence may positively affect performance comes from an experiment of Seidel et al. Seidel et al. offered students freedom of control of the topic sequence in a 30 hour course on Cobol. In this study the well-performers were found to have used this freedom significantly more than the poor-performers.

Lodewijks perceives the above quoted results as a confirmation of the idea that measures are effective to the extent to which they take individual differences in prior knowledge structure into account, or, offer the facilities to process information in a way congruent with the learner's habitual style of information processing.

#### 2.3.2.3 Regulation

Individuals create different knowledge structures and, therefore, a super-imposed sequence may not be ideal for each individual. But, the conclusion that self-imposed sequence will always lead to more effective learning is not justified either. The literature provides examples where no differences are reported, or the self-imposed condition even yields worse results when compared to a super-imposed rationale-based sequence (for a discussion see Seidel *et al.*, 1978; Alexander *et al.*, 1994). Inconsistencies in results can be due to differences in familiarity with the material. Prior knowledge not only provides anchoring points, it appears to affect regulatory capacity in general. This effect is named the *Matthew effect* (Stanovich, 1986 in Alexander *et al.*, 1994), titled after the biblical text: "For unto every one that hath shall be given, and he shall have abundance: but from him that hath not shall be taken away even that which he hath". That is, those who have achieved prior knowledge will be better able to regulate learning of related material and in consequence learn more. "Those who lack such knowledge remain unable to tackle the increasingly more demanding exposition presented to them" (Alexander et al., p. 215).

All in all, if the material is unfamiliar, the student may be unable to effectively regulate learning. Then, support in the form of super-imposed rationale-based sequence may be needed, whereas for familiar material such support is likely to cause interference. As suggested above, for familiar material autonomy may be desirable.

### 2.3.3 Learning style

Super-imposed sequence may interfere with the learner's habitual style of information processing (cf., Moore *et al.*, 1975). Self-imposed sequence may thus be more beneficial, but only if the material is relatively familiar. These were the ideas emerging from the previous sections. Aptitude-Treatment-Interaction (ATI) research has lead to a further nuance of this statement.[5]

In search for explanations for the indecisive series of scrambling and auto-determinance studies, many have suggested that aptitudes such as general ability or intelligence may have interacted with sequence (Levin & Baker, 1963; Seidel *et al.*, 1978; Lodewijks, 1983). These suggestions have given rise to several ATI studies. Although challenged by several (see e.g. Crombag, 1979), analysis of $A$-Sequence-$I$ effects appeared to be a good idea after all. For instance, the aptitude 'field dependence' (see Witkin *et al.*, 1977) was observed to be an important factor in predicting the effects of super-imposed sequence. A study by Lodewijks (1983) on physics concepts with high-school students, revealed a strong interaction of field dependence while comparing self- and super-imposed sequence. The field independent learners showed relatively high achievement in the self-imposed condition. In contrast, their achievement in the super-imposed condition was relatively low. Correction for results of a test that should provide an indication of general intelligence revealed that field dependence yielded a unique contribution to the interaction effect. Field independent learners are, by definition, likely to self-impose structure on material. In consequence, it was hypothesized by Lodewijks that the super-imposed sequence might have interfered with the habitual information processing style of the field independent learner.

A remarkable study indicating an intellectual ability - sequence interaction is that of Ferraro et al. (1977). Ferraro et al. compared achievement from logical and scrambled sequence by 1) 'educable' mentally retarded adolescents, 2) elementary school students who's mental age was representative of the mentally retarded subjects and 3) adolescents with a normal level of mental development. Only the performance of the mentally retarded was significantly enhanced by the logical sequence. Apparently, mentally retarded students were found to have different cognitive requirements in learning as compared to mental-age equivalent students. Several other studies have addressed interaction of intellectual ability and sequence (see e.g. Eylon & Reif, 1984; Mayer, 1975). These studies share the conclusion that particularly low ability students are supported by a rationale-based organization. For high ability students this is not always the case.

The studies discussed above suggest that 'aptitudes' of the learner, such as field dependence and intelligence, are to be considered when studying the effects of sequencing. Matching aptitudes and sequence should potentially lead to beneficial effects. Relevant in this respect is the work of Pask (in Entwistle, 1978) on the matching of learning styles and instructional strategy. Pask identified two learning styles on the basis of strategies adopted by students when tackling exploratory tasks, which he named a holist and serialist style. Serialists tended to follow a step by step sequence with a narrow focus, studying just one characteristic at a time. In contrast, holists tended to study larger conceptual entities, thus relating to several characteristics at a time, thereby searching for rich analogies. To study the effects of matching instructional strategy to serialist or holist learning style, Pask conducted a study that compared matched with unmatched conditions. Indeed, students

[5]Although prior knowledge (as a determinant of familiarity) is seen as an aptitude, here we will only discuss the influence of aptitudes that are more or less stable, that are less subject to change.

in the matched conditions (holists with holist materials etc.) obtained much higher posttest scores than those who had been mismatched. Once more, the conclusion is justified that learning style may affect the effect of sequencing measures.

### 2.3.3.1 Summary

**Aspects in the learner** Providing learners with a perfectly 'logical' sequence is certainly no guarantee for achievement. Several aspects in the learner affect the benefits of well designed sequence. In Figure 2.2 an attempt is made to schematically depict aspects affecting the quality of the learning process. It should be noted that only aspects and relations occur in the scheme for which empirical (or circumstantial) evidence was provided in the literature reviewed in the previous sections. In the scheme, arrows indicate influences. The numbers refer to relations described below. Where more than one aspect influences the learning process, an interaction effect may occur.

In the scheme *aspects in the learner, aspects in the sequence*, and *aspects in support* jointly influence the (quality of) the *learning process.* With aspects in the sequence, the quality of the sequence is intended, irrespective of the sequence being self- or super-imposed. This latter aspect is caught in the 'degree of guidance' in *aspects in support.*

The core of *the learning process*, that of assimilation to schema and accommodation of schemata is, amongst other things, dependent upon the quality of the learner's own *regulation* of the learning process.

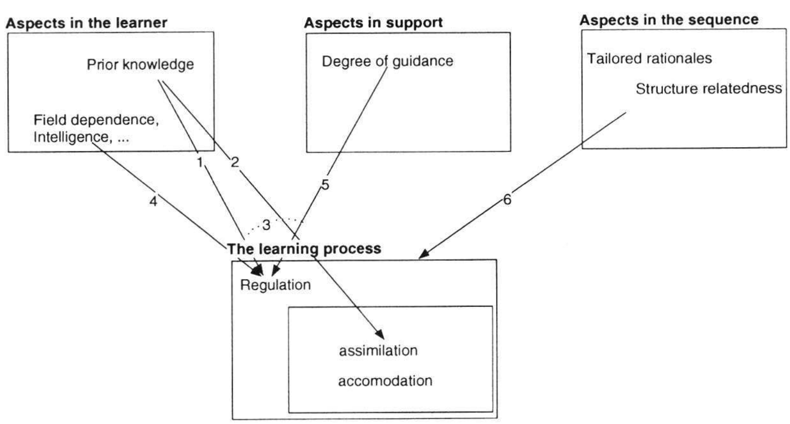



Figure 2.2: A descriptive model of some aspects in subject matter sequencing that influence the learning process

As suggested in the previous sections, *prior knowledge* is a main factor influencing the effectiveness of a sequence. Prior knowledge is argued to 1) positively affect the quality of regulation (section 2.3.2.2) as well as to be 2) a necessary condition for assimilation (section 2.3.1). 3) High prior knowledge in combination with super-imposed sequence may lead to interference (section 2.3.2.1). Aptitudes, such as field dependence, 4) influence the tendency to regulate and the quality of regulation (section 2.3.3).

Little guidance 5) requires self regulation. Whether this self regulation can be fruitful, depends on, amongst others, the amount of and quality of prior knowledge and the learner's structuring capacities.

**Aspects in the sequence** The aspects in the sequence as described in section 2.2 will be integrated in Figure 2.2. In section 2.2.2, we postulated 6) a relation between the quality of a sequence and the knowledge of structure to be acquired from that sequence. Quality of a sequence was to be expressed in terms of the degree to which rationale choice was tailored to the structures to be acquired (*tailored rationales*) and subsequently by the degree to which sequence is related to structure that acts as rationale (*structure-relatedness*).

It should be noted that negative effects of, for instance, scrambled sequence will not always manifest itself in the learning outcomes as learners with sufficient prior knowledge or strong regulatory capacities may compensate for the lack of quality of the sequence. In contrast, where material is highly familiar to the student, a structure-related sequence may well interfere with the way students normally acquire knowledge (section 2.3.2).

#### 2.3.3.2 Conclusion

**Connection to prior knowledge** As suggested in the earlier part of this chapter, the anchoring of new knowledge to previously acquired knowledge is a main concern. Several studies suggest that connecting to prior knowledge is a crucial condition for a sequence to be beneficial. Hence, any prescriptive approach to sequencing should thus:

- Facilitate the **connection to prior knowledge**

Prior knowledge may be knowledge the learner has when entering, or it may be knowledge that is gradually acquired during the session. For unfamiliar material this may imply that a sequence should be constructed so that each newly introduced topic builds upon knowledge presented earlier in the subject matter material. For familiar material, the learner should be allowed to self-impose sequence so that material can be assimilated in currently present schemata.

Where material is highly familiar to the student, a super-imposed rationale-based sequence may well interfere with the way students habitually acquire knowledge. Unfamiliar material, though, may well benefit by being prestructured. Yet, this statement can not be absolute. Several ATI studies have given rise to caution where it concerns support. For instance, with highly field-independent learners, benefits of imposed sequence are again less likely. Therefore, a next requirement is not more than a very general statement, that is, an approach should *anticipate idiosyncrasies*.

Still, for unfamiliar material and for students with low structuring capacities support remains necessary. The question is whether it is realistic to aim at the construction of teaching systems that can tailor support to the nature of the domain, learning-related aspects, and individual prior knowledge and aptitudes? At this moment instructional design theory is far from providing a solid theoretical basis for the construction of such systems. Besides, should instruction be tailored fully to the individual learner? Maybe, but we would like to quote Cronbach (1977) who pointed at the danger of 'solidifying' the global cognitive style of learners by completely tailoring education to their cognitive style.

Then, should it not be better to forget the whole idea of providing support for information space exploration, as the benefits are never evident and the danger of interference is always present?

**Non-directiveness of support** With the introduction of new media, with the increasing and often poorly organized stream of information, the demand for support will only grow. Knowing that fully tailoring the presentation to the individual learner is not realistic in the near future, one should find means for support 'that suits them all'. A key concept then is *flexibility*. The presentation of material should be such that learners with different prior knowledge and learning styles can adjust it to their own needs (cf., Merrill, 1975).

However, flexibility is all too often accompanied by lack of support. Flexibility alone is not the solution. Learners should be provided with cognitive tools that help them to regulate their learning and to grasp the structure of the material. That is, in design for support one should *anticipate idiosyncrasies by allowing flexibility*, yet one should prevent learners from loosing control by *providing support*.

- This support must then be **'non-directive'**

Non-directive support (Njoo, 1994) is unobtrusive, that is, it does not force, rather tacitly guides learners to explore in a beneficial way. When providing non-directive support, an environment should be designed so that it both helps to stay in control and that it is natural for a learner to explore in a beneficial way.

## 2.4 Conclusion: requirements for a prescriptive model

On the basis of the literature described in the previous sections, various aspects emerged that could make the difference for sequence to be beneficial or not. Statements were made on requirements for a prescriptive model stemming from differential needs of individual students, the differential nature of domains to be taught, and aspects in the learning process.

Below we will summarize the requirements:

- **Tailored rationales** In line with Posner and Strike we have argued that sequence should be logically consistent with the structure of the subject matter. A first implication is that different types of structures demand different types of rationales. In addition, different domains have different learning-related aspects. Hence, domain features and learning-related features should be reflected in rationale choice. A prescriptive model that implements a **tailored rationale** approach should make statements on which rationales to apply when, and in that make statements on *categorical dominance*. In addition, such a model should be explicit on *how to handle combinations of rationales*. A second implication is that sequence should be closely related to the structures that were chosen to act as rationales. Hence, sequence should be **'structure-related'**.

- **Connecting to prior knowledge** The anchoring of new knowledge to previously acquired knowledge is a main concern in design for beneficial sequence.

- **Support must be non-directive** An environment should offer both flexibility and support. Support should prevent learners from loosing control, besides that it should help the learner to explore in a fruitful manner. Above, we have defined 'good' information space exploration in terms of connection to prior knowledge and the combination tailored rationales and structure-relatedness. Thus, the environment must be designed so that the most natural way of exploring is one that complies with this notion of 'good' information space exploration.

# Toward prescriptions: a top-down approach

# 3

Sequence should do justice to the way people learn and develop, to characteristics of the domain as well as to idiosyncrasies of the individual learner. But, where the review of empirical studies, for instance, revealed that connection to prior knowledge is crucial for the construction of stable cognitive structures, it did not provide a clear answer on how to organize material so that such a connection could easily be established.

Several studies showed that it would be beneficial to have the rationale choice be tailored to domain-related as well as learning- related aspects. Posner and Strike provided a valuable contribution in their inventory of rationales, but they did not go beyond that. They gave no indication of when to use which rationale and how to combine different rationales. Neither did they provide prescriptions on the nature of the sequences associated with all these rationales.

No answer has been given to the question of how to provide non-directive support for information space exploration. That is, support to make learners voluntarily follow an exploratory trajectory that facilitates connection to prior knowledge as well as doing justice to the domain- and learning-related aspects that matter in learning. The review of empirical work has provided an insight into the things that matter in sequence, yet it does not go far beyond that.

A great deal of work has been done in instructional design theory to come up with prescriptions for the organization of instructional material. Much of this prescriptive theory is rooted in empirical work, some is merely based on in depth study of behavior of experienced teachers. Both sources can yield insights in how to deal with individual differences in learners, how to facilitate connection to prior knowledge, how to create structure-related sequences, etc. In the following sections, we will discuss several of the best known contributions to instructional design theory[1] that were reviewed in the hope of finding prescriptions for sequence that can comply with the requirements of chapter 2.

## 3.1 Development and learning-related approaches

"The question of how content should be sequenced has been subject to educational debates for at least the past seventy years" (Posner & Strike, 1976, p. 665). The same authors continue with "However, no satisfactory answer has been developed and no adequate prescription is expected in the near future". A long-standing controversy is, for example, the question whether the sequencing of content should be based on the substantive structure, or logic of content, or on the way in which individuals process knowledge (see e.g., Ornstein & Hunkins, 1988).

[1] In this review we have limited the discussion to the so called macro level of sequencing. Therefore, prescriptions for the sequencing of examples such as in (Collins & Stevens, 1983) and (Merrill, 1983) are outside the scope of this discussion.

### 3.1.1 The Soviet psychologists

Those arguing for sequence based on psychological principles draw on theories on human growth, development and learning. For example, Piaget's research (in McCarthy Galager & Reid, 1981) has provided a framework for sequencing content and activities based on an understanding of how individuals function at various cognitive levels. The great names of the Soviet psychology have provided us with valuable ideas on sequencing based on stages of development. Vygotsky (in van Parreren & Carpay, 1980), for instance, claimed that acquisition of skills goes via a number of distinct stages of development. Main point in his theoretical work is that instruction should not focus on the current factual level of development, but that it should always anticipate on the next higher level of development. Instruction should try to stimulate the transition to this higher stage.

With the work of Vygotsky as a basis, Gal'perin elaborated on the theory of stages of development, and developed the famous and well validated stair-wise model that prescribes a sequence of orientation, material manipulation, verbal manipulation, interior verbal manipulation and subsequently mental manipulation (see van Parreren & Carpay, 1980). Both Vygotsky and Gal'perin thus prescribe a sequence where each next stage builds upon the skills acquired in previous stages, hence such sequence aims at *connecting to prior skills*.

**Discussion** Gal'perin promoted a highly *directive* form of instruction. Instruction was to be delivered in the form of practice and drill, assuming error-free learning. Kamsteeg (1994) remarks that such methods are likely to be inadequate for learning complex tasks such as problem solving. The work is thus assumed to be limited in scope. It also received comments on its fundamental assumptions. Where Gal'perin focused on the psychological analysis of learning results and the processes that lead to it, Davydov (again van Parreren & Carpay, 1980, p. 99) criticized the lack of attention paid to logical analysis of the subject matter. Davidov conducted several experiments with sequences based on domain-related rationales. This work lead him to the conclusion that instruction should be structured so that maximal attention should be addressed to domain-related aspects of the subject matter. In our view, both standpoints should get the recognition they deserve and might eventually be combined. The requirement of *tailored rationales* implies that, when organizing content into a productive sequence, it is not right to disregard how individuals develop and learn. Nor can the domain-related aspects be neglected.

### 3.1.2 Gagné: Learning hierarchies

Where Vygotsky and Gal'perin provided prescriptions for a development-based approach to sequencing, Gagné suggested a primarily learning-related approach (see Gagné *et al.*, 1988; Gagné, 1962; Aronson & Briggs, 1983). This approach is commonly known as 'cumulative learning' or 'prerequisite-first learning'. Gagné suggested the construction of so called 'learning hierarchies'. Such a learning hierarchy was formed by breaking up intellectual skills[2] into simpler component parts. These component parts are seen as prerequisite to the acquisition of the target skills. Thus, the parts need to be taught prior to the compound skills, that is, the sequence takes a bottom-up direction.

[2] Intellectual skills form just one of the categories of learning outcomes as distinguished by Gagné. For other categories, such as motor skills and cognitive strategies, slightly different sequencing principles are proposed. Still prerequisite learning is the most important ingredient.

**Discussion** The validity of this hierarchical sequencing technique is certainly not beyond question. Firstly, when focusing on the learning effects of the application of the method, results are inconclusive. In favor of careful sequencing of prerequisites is a study by (Gagné & Paradise, 1961, as cited in Patten *et al.*, 1986). In this study it was found that teaching prerequisites first appears to facilitate the acquisition of higher order skills more than teaching prerequisites out of sequence. The same was true for a study by Brown (1970) who, while searching for ATI effects, found a main effect of prerequisite-first sequencing. In contrast, two other studies (Pyatte, 1969; Niedermeyer *et al.*, 1969) reported no main effects of careful sequencing using a prerequisite-first rationale.

Secondly, a fundamental critique should be put forward. As 'cumulative learning' reflects a bottom-up sequence, such sequence may fail to establish 'meaningful learning'. Learners start learning isolated skills, to only learn the target skill at the very end of the course unit. The question is whether isolated skills make sense without careful *connection to the previously learned*, as, for instance, in progressive differentiation (Ausubel, see section 3.2.1). Unlike the other prevailing theories discussed here, Gagné's work suggests only meager means for providing a meaningful context for learning.

In our view, a particularly elegant solution where not yet mastered prerequisites do not prevent from teaching the whole picture, is that of 'scaffolding' (Collins *et al.*, 1989). In scaffolding, an expert takes over the subtasks not yet mastered by the student, thus allowing the student to still perform the whole target task. As the student learns more of the prerequisite skills, the expert fades, that is, decreases the amount of scaffolding provided (see also section 3.3.1).

The work of Gagné still is an important contribution to the field of sequencing in stressing the necessity of task analysis. Gagné has clearly shown (see Gagné, 1962) that teaching a complex task is likely to fail due to lack of prior knowledge. But, as Reigeluth and Stein (1983) claim (p. 339), a microscopic analysis of prerequisite relation is of questionable utility to instructional developers. It is extremely time consuming to represent subject matter in a manner prescribed by Gagné (see Lodewijks, 1983). It is equally time consuming and difficult to decide on sequence on the basis of such a detailed learning hierarchy. The latter is not a convincing argument to reject the use of prerequisite-first rationale as a main organizing principle. A more ponderous argument is that, besides the prerequisite relation, other kinds of relationships between skills are taught that influence the kind of a sequence that will best facilitate learning (see Posner & Strike, 1976). Gagné's approach will mask the conceptual and logical properties of content (see Strike & Posner, 1976). Hence, it does not *tailor rationales* to the nature of subject matter. As Reigeluth (1983) puts it: Prerequisite learning is a necessary, but not a sufficient basis for sequencing content.

### 3.1.3 Bruner: The spiral curriculum

Where Gagné advocated a bottom-up approach, Bruner suggested a highly top-down approach to sequencing, which he named the Spiral curriculum (Bruner, 1960; Bruner, 1966). Bruner was one of the main characters in a curriculum reform movement during the late fifties and the early sixties. This movement advocated an often termed 'structure of the disciplines' approach. Central in this approach is, as in the Spiral curriculum, that authors try to find the 'few fundamental ideas' that outline the 'structure of a discipline'. Sequence is built around these fundamental ideas. The same fundamental ideas are taught over and over, but each time at an increasing degree of complexity and sophistication. With this iterative cumulation, *connection to prior knowledge* should be established.

Bruner contended that if a topic was really important for a learner to know, it should be introduced in education as early as possible. As students become more intellectually mature, their understanding of the topics should develop and get more and more sophisticated. In the tradition of the early Soviet pedagogues, content should be sequenced 'commensurately' with the learner's level of intellectual development.

**Discussion** A major assumption underlying the Spiral curriculum is that "any subject can be taught effectively in some intellectually honest form to any child at any stage of development" (Bruner, 1960, p. 13) has been challenged. "It is not obvious that any idea can be plausibly represented in a form so as to render it comprehensible to any given stage of development" (see Strike & Posner, 1976, p. 120). Bruner, however, responds in the 1977 preface to his 1960 work by saying that the notion 'intellectual honesty' was gravely misinterpreted. Not the central notions, but the skills and ideas that are prerequisite to an understanding of those notions are to be taught. With this we conclude that the main underlying rationale is a developmental/learning-related. That is, Bruner has acknowledged the need for thorough domain analysis, but does not apply domain-related rationales to sequencing.

Little can be said concerning the validity of the approach as "empirical research and evaluation studies [of the Spiral curriculum] have been and continue to be few in number and poor in quality" (Strike & Posner, 1976, p. 119). What may have contributed to this, as van Patten (1986) concludes (p. 446), is that the approach can be difficult for an instructional designer to implement, because Bruner "did not provide enough guidance as how to create a spiral curriculum".

## 3.2 Toward integrative approaches

### 3.2.1 Ausubel: Progressive differentiation

Vygotsky, Gal'perin and also Bruner adopted an approach that was mainly development and/or learning-related. Ausubel mainly suggests domain-related rationales for sequencing, more in particular, a rationale that relates to the conceptual structure of the subject matter. This difference in stance may be partly explained by the fact that theories of Vygotsky and Gal'perin seem to have primarily addressed the development of the younger child. In the experiments that were set up to test the assumptions of, for instance, the work of Ausubel, the participants were mainly adolescents or adults. Instruction for this group usually addresses the highest levels of development only. Level of development as rationale is then a less likely choice.

Ausubel insisted that effective curriculum organization should take into account the logical features of the subject matter. Ausubel's approach is based on his theory of learning that assumes that cognitive structure is "hierarchically organized in terms of highly inclusive concepts under which are subsumed less inclusive concepts and informational data" (Ausubel, 1960, p. 267). A review by Eylon and Reif (1984) of studies on hierarchical organization indeed suggests some support to this assumption.

According to Ausubel, sequence should reflect this hierarchical organization. Sequence should take a top-down direction, start with high level, inclusive concepts in a domain and progressively introduce the subsumed concepts. The 'logical' structure of a domain is thus restricted to a hierarchical class-inclusion[3] organization.

[3] According to an interpretation of Strike and Posner (1976)

Main theme in the work of Ausubel is 'meaningful reception learning'. Meaningful reception learning implies that new knowledge should never be presented in isolation, it should be closely *connected to prior knowledge*. The instructional measures of Ausubel's approach all aim at providing 'organizing structure' for the assimilation of new knowledge. 'Advance organizers' for instance "bridge the gap between what the learner already knows and what he needs to know before he can meaningfully learn the task at hand." (Ausubel *et al.*, 1978, p. 171). According to Ausubel, a course should start with general and inclusive ideas that serve as (advance) organizer for the next levels of detail and specificity. As the learner descends to lower levels, the ideas provided in the organizer are supposed to act as anchoring points for the assimilation of the concepts that reside at those lower levels. This does not only hold for the first level, each level is supposed to act as an organizer for its next lower level. Such a layered organization of the subject matter guarantees a so called 'progressive differentiation' of the initial ideas. Finally, 'integrative reconciliation' is facilitated if the instructional material anticipates on "the confuseable similarities and differences between new ideas" (Ausubel *et al.*, 1978, p. 116). In this, learners should be aided in resolving what may appear to be inconsistencies or conflicts between existing and new concepts.

Referring back to the requirements for a prescriptive theory, Ausubel's notions of 'advance organizing' and 'progressive differentiation' may provide an answer to the question of how to meet the requirement of *facilitating the connection to prior knowledge.*

**Discussion** According to (Mayer, 1978, p. 880) "there is lack of agreement concerning the empirical support for the effects of advance organizers". Mayer lists many reported cases of organizers positively affecting performance (see e.g. Mayer, 1977) but also some cases where these do not have any positive effect. Hypothesizing that advance organizers are only effective under certain circumstances, Mayer conducted a series of experiments to test some of the assumptions of the approach. This series of studies clearly supports the conclusion that advance organizers indeed have a positive effect when the material is technical and unfamiliar to the student (see also section 2.3.1). In addition, Mayer (1978) found an interaction effect for text organization, namely that providing an advance organizer to well organized text leads to detrimental results, whereas the same organizer was beneficial to scrambled text.

All in all, not all experiences with the use of advance organizers are positive. Apparently, advance organizers have benefits under those circumstances where support is needed most, that is, with badly organized, technical, or unfamiliar material. With respect to progressive differentiation, de Jong (1986) points at a danger of providing learners with a hierarchical organization. He argues that this may well exceed their capacities. For novices, a problem directed organization might well be a useful intermediate stage toward expertise.

Still, the work of Ausubel, combined with the empirical work of Mayer, is recognized as an important contribution to the field. More recent prescriptive models all provide means to facilitate *the connection to prior knowledge.* Where the ideas are an important contribution, the operationalization of prescriptions has been subject to considerable criticism. "The theory is often excessively vague" (Strike & Posner, 1976, p. 123). In addition, many have criticized the narrowness of subsumption as only mean to establish connections to prior knowledge. In their Elaboration theory, Reigeluth and Stein (1983) have both attempted to come up with a broader view on progressive differentiation as well as with more operational definitions of the dimensions of progression (section 3.2.2). The elaboration theory was built on foundations laid by Ausubel. In addition, it used some bricks from the work of Gagné on 'prerequisite-first learning'.

### 3.2.2 Reigeluth et al.: The Elaboration theory

The Elaboration theory (Reigeluth & Stein, 1983; Reigeluth, 1983; Merrill *et al.*, 1981; Reigeluth *et al.*, 1978) integrated elements of the approaches discussed above. In the Elaboration approach, a lesson is supposed to start with an 'epitome' which has much of the flavor of the advance organizers as suggested by Ausubel. An epitome includes a few fundamental and representative ideas that convey the essence of the entire content (as in the Spiral Curriculum). Rather than being a summary at a rather abstract level, an epitome is supposed to provide a simple, concrete and meaningful introduction at the application level of learning (see Merrill, 1983). That is, an epitome may introduce a few fundamental principles in a way that the student is able to predict or explain novel cases on the basis of just this knowledge. The ideas of Progressive differentiation or Spiral curriculum find their descendent in 'elaboration'. In elaboration, a course is constructed by means of several levels, where each level 'elaborates' upon the next higher level. That is, from the epitome, each next level provides more detail and more complexity. A hierarchical rationale is thus applied for coarse-grained organization.

As in progressive differentiation, each level is supposed to provide a meaningful context to the next lower level. A level may contain one or more lesson units that each are composed of a number of 'strategy components'. The elaboration approach, for instance, prescribes providing analogies, summaries and even more importantly, so called 'synthesizers'. Synthesizing specifically aims at integrating the individual ideas by showing how they fit into the larger picture. By this, synthesizing is highly similar to Ausubel's integrative reconciliation.

Finally, prerequisite learning, as suggested by Gagné, is introduced, although, not as a main guiding principle. Prerequisite learning is only applied within lesson units when necessary and is thus used for fine-grained organization only. At a coarse-grained level of organization, a hierarchical rationale thus takes *categorical dominance* over a prerequisite rationale.

Reigeluth and co-workers not only integrated and extended elements from other prescriptive theories but also provided an important contribution to the field by providing operationalizations for *structure-related* sequence. This description for a structure-related sequence covers an elaborative, general-to-specific sequence imposed upon hierarchical structure. Reigeluth's operationalization of the elaborative sequence varies considerably according to whether the levels in the hierarchy consist of conceptual, procedural, or theoretical (the latter consists of causal relations) structure.[4] For instance, for procedural structure the epitome would provide a procedure that consists of a set of operations that constitute the shortest path to successful performance. Elaborations would then introduce more complex procedures. An example of such an elaboration in, for instance, the take-off procedure in pilot training, would be to start with this procedure under ideal circumstances, while later on progressively introducing bad weather conditions, busy traffic, and emergencies. For each of the types of organizing content, different operationalizations are given.

**Discussion** It should be noticed that the sequences prescribed are different operationalizations of the same general-to-specific sequence. These different prescriptions for sequences are thus based on a single rationale and by that do not comply with the requirement of *tailored rationales*. Rather,

[4]Close cooperation with the founder of the Component Display Theory (Merrill, 1983, see also Reigeluth *et al.*, 1978) resulted in an identification of three types of 'organizing' structures. Reigeluth et al. distinguish conceptual, procedural, and theoretical single type structures. The motivation for the use of single organizing structure is that "careful analysis has shown that virtually every course holds one of these three to be more important than the other two." (Reigeluth, 1987, p. 248).

by providing prescriptions for sequence that closely relates to the hierarchical structure that acts as rationale, the approach complies with the requirement of *structure-relatedness*. Reigeluth et al. do, however, take a first step toward *tailored rationales*. They remark that, within a level of elaboration, content must also be sequenced and consequently provide an example for procedural structure. In the example, procedural structure itself acts as rationale. Reigeluth et al. thus recognize that different types of structure require different sequencing rationales.

In summary, the Elaboration theory has provided more operational definitions to Ausubel's advance organizing,[5] progressive differentiation. It provides prescriptions for *structure-relatedness* of sequence organized by a hierarchical rationale. Besides, Elaboration theory was the first to do justice to the logic of the substantive structure of domains. Elaboration theory recognizes that different types of structure require different sequencing rationales. Hence, the elaboration theory attempts to meet both the requirement of facilitating *connection to prior knowledge* and to provide prescriptions that *tailor rationales* to structure of the subject matter. Besides this, it allows the combination of an elaborative and a learning prerequisite sequence and does make statements on categorical dominance.

With respect to its validity, the Elaboration theory "has been one of the best-received theoretical innovations in instructional design in the last 15 years and is frequently referred to and used by practitioners and researchers" (Wilson & Cole, 1992, p. 1). But again, its validity is not beyond question. Smith and Wedman (Smith & Wedman, 1988, referred to in Wilson & Cole, 1992), for instance, compared instruction organized both on the basis of the Elaboration theory and on the basis of the learning hierarchy approach of Gagné. Unexpectedly, the latter lead to a better processing of the subject matter material.

As currently best known theory in this area, the Elaboration theory has given rise to much debate. Several authors have objected to fundamental assumptions underlying this 'instructivist' theory. As Bereiter (1991) puts it (p. 15): "this family of instructional theories has produced an abundance of technology on an illusory psychological foundation". This illusory foundation is the assumption of the possibility of discretely dividing knowledge into, for instance, concepts, procedures, and principles. Others have stressed that learning is the becoming part of a community which jointly constructs meaning. From this point of view, the context of use becomes part of the content structure (see e.g. Collins *et al.*, 1989). This stance indeed leads to major disagreement, as Merrill (1991) responded (p. 47): "We do not assume that the resulting cognitive structure is completely idiosyncratic. We assume that the semantics of content of cognitive structure is unique for each individual, but that the syntax is not." In consequence, the 'instructivists' assume that the syntax of knowledge can be known and used to tailor instruction.

The question whether knowledge can and should be presented in a decontextualized way has been subject to much discussion (see Elshout, 1990; Sandberg & Wielinga, 1992). Rather than fully rejecting one of the stances, some have seen possibilities for approaches to converge (Wilson & Cole, 1992; Sandberg & Wielinga, 1992). Indeed, traditional 'instructivist' theories seem to pay growing attention to realistic experience. On the other hand, Collins, exponent of the constructivist movement, has recently recognized the need for more emphasis on decontextualization in the cognitive apprenticeship approach (section 3.3.1).

A second criticism is hardly less fundamental. Reigeluth claims that all instructional content can be represented using just three structure types. With this, the Elaboration theory's constrained approach to content representation provides parsimony to its procedures, but at what costs? Ex-

[5]Though slight differences exists in the definition of advance organizer and that of an epitome (see Reigeluth, 1983, p. 211)

ercises in the construction of representation languages for conceptual modeling have shown that users readily stumble upon the limits of expressiveness of languages that use a limited, nonextendible set of primitives (Levesque & Brachman, 1985; Brachman *et al.*, 1985). A question is whether such a restricted set of structure types will not be detrimental to curriculum organization. Evidently, experienced teachers use a richer set of structure types on which they base their decisions with regard to sequence (see e.g., Posner & Strike, 1976). In addition, according to Wilson and Cole (p. 4) "there seems to be little evidence to draw on in psychology literature to support such a constrained approach to course organization".

The Elaboration theory was the first to provide operational prescription that did not violate the requirement of tailored rationales. The three structure type basis of the theory is in our view, however, too restrictive. In chapter 4 we will discuss a richer and extendible set of rationales for decision making on sequencing.

## 3.3 Specialized approaches

The prescriptive approaches discussed in the previous sections all more or less aimed at general applicability. In the following sections, we will discuss two approaches that have been described with a special intention. A first is the cognitive apprenticeship approach, that aims at supporting the acquisition of cognitive skills. A second is the model progression approach that is described with a subset of domains in mind. This subset is limited to causal domains.

### 3.3.1 Collins et al.: The cognitive apprenticeship approach

A recent contribution to the field is the cognitive apprenticeship approach (Collins *et al.*, 1989; Brown *et al.*, 1989). As a product of the constructivist and situationist movement it is said to be based on quite different assumptions about the nature of learning as compared to the more traditional instructional design theories. Indeed, the approach provides numerous recommendations for constructing realistic practice, the prescriptions for sequencing are, however, not so far from those of the Elaboration theory (see Wilson & Cole, 1992).

The cognitive apprenticeship approach tries to extrapolate the well proven apprenticeship method to the teaching of cognitive skills. The traditional apprenticeship method can roughly be characterized by demonstration, providing practice, and coaching. The apprentice observes the master 'modeling' the target task. The apprentice is made to execute the task with coaching from the master. A key aspect of coaching is the provision of 'scaffolding'. Here, the apprentice carries out the task while the expert takes on whatever portion of the task the apprentice cannot handle. Once the learner has a grasp of the target skill, the master 'fades' (i.e., reduces) his participation, while providing only limited hints, refinements, and feedback to the learner. The learner thus practices by 'successive approximation' smooth execution of the whole skill.

The traditional apprenticeship method is not directly applicable to the teaching of cognitive skills. Apprenticeship is traditionally employed to transmit pycho-motor skills. The analogy between those skills and cognitive skills fails because the steps and results of non-cognitive skills are readily available for observation, whereas those of cognitive skills are mostly internal. As a transparent connection between process and product lacks, it is difficult for learners to monitor and to reflect upon their own performance. In consequence, the cognitive apprenticeship approach proposes several strategy components "to bring the tacit processes in the open" (Collins *et al.*, 1989, p. 458). Reflection is encouraged by 'alternation' of task execution between expert and novice. A technique named 'abstracted replay' has the same intention. Abstracted replay focuses on determining features of both learner (novice) and expert performance by highlighting those features in, for instance, a skillful verbal description. With respect to sequencing, the method suggests several coaching techniques that provide an operationalization of several of the pervasive ideas on sequencing as were presented in section 2.3.3.2. According to Collins et al., the idea of advance organizing takes shape in the form of 'modeling'. Modeling, a skilled expert performing the task, is supposed to provide the apprentice with a conceptual model of that task. This model is said to fulfill many of the functions earlier attributed to advance organizers. It is claimed 1) to provide an interpretative structure for making sense of the feedback, hints and corrections provided by the expert, 2) to act as an internalized guide for the period of relative independent practice and, by that 3) encourage autonomy in reflection.

Modeling is followed by a period of coached practice. This practice is organized according to the principle of 'successive approximation' of mature practice. Students are 'scaffolded' to perform a target task in close cooperation with an expert. That is, the expert initially takes over a lot of the subskills that are not yet mastered by the learner. In due course, this scaffolding is gradually diminished and the learner takes over more and more of those subtasks. The sequencing of subtasks is prescribed to be in accordance with a 'global-before-local' principle. For instance, in learning to program, the apprentice is first offered practice in designing the overall program structure while successively the construction of the composing procedures is practiced, again within the context of the overall program. This global-before-local principle is supposed to provide the learners with the opportunity to see how all the pieces of the puzzle fit together before they are able to produce the pieces.

It should be noted that the 'global-before-local' prescription is directly opposite to Gagné's prerequisite-first approach. As Gagné did not anticipate scaffolding, all subskills had to be mastered by the learner before the global skills could be practiced anyway. The global-before-local sequence is highly similar to progressive differentiation and may therefore facilitate *connection to prior knowledge*.

Where scaffolding and fading aimed at a single task, the cognitive apprenticeship approach also provides prescriptions for sequencing a series of tasks. Tasks should be ordered from simple to complex and should be of increasing diversity. Increasing complexity is realized by the construction of a series of tasks and task environments (cf., White & Frederiksen, 1990) where more and more of the skills and concepts necessary for expert performance are called upon. Evidently, this is in line with principles for sequencing procedural content as proposed by Reigeluth.

Where all previous principles aim at helping learners to understand how to apply skills, the principle of 'increasing diversity' aims at making them aware of the circumstances when to apply a skill. It is put into practice by providing a sequence of tasks in which a wider and wider variety of the target skills are required.

**Discussion** As other well known theories, the cognitive apprenticeship approach has been subject to discussion. Discussion, however, is more focused on the underlying constructivistic assumptions with respect to learning than on the principles with respect to sequencing (see e.g., Duffy & Jonassen, 1991).

De Bruijn (1993) implemented several of the key concepts of cognitive apprenticeship in a computerized environment for adult learning of a mathematics task. A general idea that emerges from this study is that the subjects were not too eager to use the support in the form of coaching and modeling. On the other hand, reflection seemed to come naturally by being supported with 'abstracted replay' in the form of a so called 'audit trial', a history that allows the learner in this case to look back on the steps in the process. Finally, articulation of their own problem solving process in a cooperative situation was relatively rare. It should be noted that the subjects were functionally illiterate and were assumed to be incapable of self-regulating their learning. This makes it difficult to generalize results where making statements on the feasibility of the cognitive apprenticeship approach.

In the light of the requirements for a prescriptive model, Collins et al. (1989) acknowledged the necessity of *connecting to prior knowledge* through modeling and the tailoring of support to the individual learner. However, their prescriptions do not go beyond this acknowledgment. How to provide individualized fading, practice, and coaching is left to the master.

### 3.3.2 White and Frederiksen: The model progression approach

The final approach reviewed here is the 'model progression' approach as described by White and Frederiksen (Frederiksen & White, 1988; White & Frederiksen, 1989; White & Frederiksen, 1990). This approached is limited to use in causal domains only. Though it is not generally applicable, several of the ideas might be used outside the scope of causal domains. In this chapter we will only briefly discuss a few of the characteristics of this approach, a more elaborate description can be found in chapter 7.

The model progression approach implements several of the aspects recognized to be essential for effective sequencing. Model progression provides a learner with a series of increasingly sophisticated 'work' models (cf., Bunderson *et al.*, 1981). By starting with less sophisticated models, much of the complexity of the target model is initially hidden. Those initial models are supposed to facilitate establishing a *connection between the learners naive preconceptions and the conceptions to be acquired.* Then, by gradually increasing complexity and shifting from qualitative to quantitative models, each work model builds upon the conceptions derived from previous models.

The model progression approach aims at providing an exploration space that is manageable at the student's current level of understanding. Each work model contains much of the previous work models and only introduces a few new topics. The idea is that within such a relatively familiar environment students should be able to regulate their own learning. Indeed, as postulated in section 2.3.2.2 and shown amongst others by Shute and Glaser (1990), the more students know about a model, the better they are able to regulate their exploration. With relatively little unfamiliar material in each work model, regulation should be manageable.

In model progression, guidance is provided at a global level where freedom is granted at a local level. The hope is that this local freedom does sufficient justice to idiosyncrasies of learners while support at a global level helps to keep the local environment manageable. The environment is thus tailored to the learner's current abilities and with this, model progression complies with the requirement of *non-directive support.*

Finally, the model progression approach is with the Elaboration theory one of the few prescriptive theories that prescribes a multiple rationale approach and with that, does not violate the requirement of *tailored rationales*. The approach defines three so-called 'dimensions' along which models should progress. It should be noted that the notion of dimension in this context is similar to that of rationale. The prescriptions for sequences of models both reflect an awareness of learning-related aspects such as differences in complexity, as well as domain-related aspects as present in a qualitative-to-quantitative and perspective-based sequence.

**Discussion** In our view, the model progression approach came closest to meeting the requirements stated in chapter 2. It does anticipate connection to prior knowledge and it reveals sensitiveness to domain-related aspects as well as learning-related aspect of the target domains. Besides, it was perceived as a potentially powerful method of providing non-directive support leading to a manageable environment.

A problematic aspect is that the prescriptions are described in domain specific terms, that of the domain of circuit theory that was used as an illustration. Such domain specific prescriptions are not readily applied in a different context. In addition, it should not be forgotten that the application of the approach was limited to causal domains only, thus suitable for support of simulation-based exploratory learning but not readily outside that area.

To our knowledge, only one empirical study on the effects of application of a model progression approach was conducted. This was a study by Veenman (1990; 1993) in the domain of circuit theory with freshmen psychology students. Veenman provided his subjects with a sequence imposed upon a qualitative-quantitative rationale. This study failed to reveal benefits of such a type of model progression.

## 3.4 Conclusion

This chapter ends with a reflection on the prescriptive theories in the light of the requirements as listed in chapter 2. As summarized in section 2.4, for a prescriptive model to be potentially effective, it should at least take into consideration the following requirements: 1) It should provide means to *connect new material to prior knowledge*. 2) It should contain prescriptions that lead to sequences that are logically consistent with the structure of the subject matter, as well as take into account learning-related aspects of domains, hence provide *tailored rationales*. A related requirement was that sequence should be closely related to the structures that act as rationale, in other words be *structure-related*. 3) A final requirement is one upon the nature of support to be provided. Support should be *non-directive*. It should take into account idiosyncrasies of learners by allowing a certain level of flexibility, yet provide tacit guidance so that connection to prior knowledge is established and that learners explore in such way that the exploratory trajectory closely relates to structures that reflect empirical properties of the domain and does justice to learning-related aspects.

### 3.4.1 Connection to prior knowledge

If one thing is well worked out in the prescriptive theories described in this chapter, it is providing *design constructs* that aim at establishing a connection to prior knowledge. As remarked in section 3.1.2 only Gagné's 'prerequisite-first learning' is not directly dedicated to the facilitation of anchoring of new knowledge.

Main ingredients of design constructs that aim at connecting to prior knowledge are forms of *advance overview* combined with sequence that aims at *'iterative cumulation'* of knowledge.

**Advance overviews** Advance overviews are, for instance, materialized in Ausubel's 'advance organizers', Reigeluth's 'epitome' and the 'modeling' in the work of Collins, Brown, and Newman. In essence, these overviews are said to aim at activating relevant prior knowledge as well as act as a framework for the anchoring of new material. The most explicit prescription for the construction of such advance organizers can be found in the work of Reigeluth et al. (1983), (p. 344).

**Iterative cumulation** Iterative cumulation of knowledge is manifest in Bruner's 'spiral curriculum', Ausubel's 'progressive differentiation', Reigeluth's 'elaboration', White and Frederiksen's model progression and, for the work of Collins et al. though less directly, in the combination of scaffolding and fading while using a global-to-local sequencing principle. In addition, Vygotsky's and Gal'perin's prescriptions for sequence along stages of development can be seen as a form of iterative cumulation that builds upon prior levels of development.

Various forms of iterative cumulation are found. White and Frederiksen, for instance, prescribe a sequence of models where the previous model frequently is part of a next model. A second form is provided by Ausubel and Reigeluth et al. They prescribe that a hierarchical structure is to be imposed on the domain. This hierarchical structure is then taken as a rationale for a general-to-specific sequence. Within the sequence, each level is then connected to previous levels, since being a specialization of those previous levels. The global-to-local sequence of Collins et al. is very similar to the hierarchical rationale based general-to-specific sequence, though not entirely identical.

Eylon and Reif (1984) provided some evidence that a hierarchical rationale based general-to-specific sequence, as the ones proposed by Ausubel and Reigeluth, when compared to a sequence that provides a specific level only, can "appreciably facilitate educationally important recall" (p. 39). In consequence, a hierarchical rationale based general-to-specific sequence is seen as a potentially valid operationalization of the notion of iterative cumulation.

### 3.4.2 Tailored rationales

Meaningful learning, or connecting to prior knowledge, is evidently assumed to be one of the most important aspects to be established in sequencing, if not the most important (cf., Ausubel *et al.*, 1978). Still, a focus on connecting to prior knowledge may have obscured another issue, that of tailored rationales.

**A multiple rationale approach** If one compares the set of rationales that are suggested in the theories reviewed with the entire set of rationales for sequencing content as mentioned by Posner and Strike (1976), the only conclusion can be that the majority of theories ignores both characteristics of domains and (aspects of) the learning process.

Vygotsky, Gal'perin, Gagné, Bruner and Ausubel prescribed single rationale-based sequence. A single rationale-based approach inherently cannot satisfy the requirement of tailored rationales. Reigeluth et al. and White and Frederiksen prescribed a multiple rationale approach. However, the work of Reigeluth et al. is based on a very limited set of possible knowledge structures. With that, the resulting set of rationales suggested is much smaller than the one suggested by Posner and Strike. Finally, White and Frederiksen provide prescriptions for use of rationales that are tailored to both domain and learning-related aspects of the intended subject matter. As their work is restricted to causal domains only, no general statements may be derived from it.

An omission in the work of White and Frederiksen is that they make no statements on *categorical dominance* nor on the *combination of rationales*. Reigeluth et al. on the other hand, do make such statements. With respect to categorical dominance, a distinction is made between overall organization, for which the hierarchical rationale is dominant, and organization within levels of the hierarchy where prerequisite-first, procedural and causal rationales are dominant. A distinction between overall organization and within level organization is part of an answer to the question of how to combine sequences based on various rationales.

Reigeluth's statements on categorical dominance and combining rationale are restricted to a very limited set of rationales, hence no general statements can be made on when to apply which rationales, on categorical dominance and on how to combine several rationales.

**Structure-relatedness** Only the Elaboration theory provides prescriptions for structure-related sequencing that are sufficiently explicit. Reigeluth prescribes the exact nature of a hierarchical rationale-based general-to-specific sequence. This sequence takes a top-down direction where the hierarchical structure is descended in a combined breadth- and depth-first manner. The sequence described here is highly structure-related in that it by all means tries to stay close to the structure. Large 'jumps' through the structure are scrupulously avoided and are made only to arrive at other branches of the hierarchical structure.

The aforementioned prescription for hierarchical rationale-based general-to-specific sequence is not more than an illustration of what structure-related sequence could be like. Again no general statements can be made on the nature of structure-related sequence.

### 3.4.3 Non-directive support

Most of the contributions to instructional design theory were founded in the context of written instruction or programmed instruction. This tradition was one of little flexibility; books are generally read from the beginning to the end and the programmed instruction of those days was rigid in its subject matter sequence. Hence, the approaches such as those of Gagné, Bruner, Ausubel and to a lesser extent that of Reigeluth, tend to have a bias towards directive forms of instruction. Consequently, they mainly aim at prescribing an 'optimal' path through the material, a single best approach to sequencing.

In section 2.3.3 we have argued that there is no such thing as a single optimal approach to sequencing. Accumulating evidence suggests interactions between sequencing variables, prior knowledge, and characteristics of the learner. None of the theories has made attempts to model those interactions, let alone has tried to provide prescriptions that aim at tailoring sequence to individual differences.

Some more recent approaches allow adjustment to individual needs, yet fail to specify how to tailor sequence to individual differences. The cognitive apprenticeship approach assumes an apprenticeship-master situation and thus inherently addresses individual differences. The master is supposed to adjust the coaching to the needs of the student. However, decisions on the type of support to be given to, for instance, a field dependent student, are all put in the hands of the coach. Certainly, an experienced human coach might not need prescriptions to guide those decisions. However, for the construction of prescriptions that will underly computer supported instructional design, unambiguous, operational principles are a must. Hence, the cognitive apprenticeship approach is in this respect also not of much help.

The model progression approach is closest to meeting the requirements. It suggests the realization of an environment that provides support at a global level but leaves freedom at a local level. If well designed it might do justice to the requirement of non-directive support. Still, this approach too lacks concrete prescriptions on the amount of freedom, the number of new topics to be introduced in each new model.

### 3.4.4 On the nature of a prescriptive model

Much of the critique found in the literature related to the vagueness of the prescriptions in the various theories. Van Patten's critique on Bruner was still modest, as Bruner "did not provide enough guidance as how to create a Spiral curriculum" (section 3.1.3). Strike and Posner did not even try to be subtle when referring to the work of Ausubel "The theory is often excessively vague" (section 3.2.1). Indeed, vagueness of many of the prescriptions made analysis of those prescriptions in terms of requirements an awkward exercise.

Many of the prescriptive theories reviewed were so-called first generation[6] instructional design theories. First generation theory is relatively coarse-grained of nature. Such theory provides a small number of rather general principles that are geared towards human instructional designers. Human instructional designers generally can cope with relatively vague prescriptions.

In the study documented in this thesis, however, we did not aim at providing a prescriptive approach for human instructional designers. The intention was to produce prescriptions for computer supported design. For those purposes, a prescriptive model could and should be finer grained. In addition, for a model to be non-ambiguous it had to be defined only in terms of elements known to the system.

Thus, during the analysis of prescriptive theory an additional requirement for a prescriptive model emerged. This requirement concerned not so much the content of a prescriptive model, rather than the form of such model. A prescriptive model should provide prescriptions that are *non-ambiguous*.

In the present chapter, we attempted to extract prescriptions and design constructs from currently available prescriptive theory. What could be extracted from those theories, was generally put in relatively vague terms. In the following chapter a bottom up approach is applied resulting in prescriptions that would be finer grained and less ambiguous, thus suiting a computer based approach for support.

[6]The distinction between first and second generation instructional design theory was originally made by Merrill (1990).

# Part B

The previous chapters reviewed literature to survey possible requirements for support, and sketched some of the present prescriptive approaches in the light of these requirements. A conclusion was that the model progression approach came closest to meeting the requirements. It was assumed to anticipate connection to prior knowledge and to reveal a sensitiveness to the requirements of tailored rationales and structure-related sequencing. Finally it was assumed to prescribe a form of non-directive support.

While anticipating effort on operationalization and formalization, the model progression approach was decided to be a good candidate for support for information space exploration within the scope of simulation-based learning. Part C thus describes the operationalization, implementation and evaluation of this approach. Part of the study reported here, however, aimed at investigating options for support of information space exploration that would be generally applicable.

None of the generally applicable prescriptive theories met all requirements to a sufficient extent. It was therefore decided to try to construct a prescriptive model by integrating ideas from the various prescriptive theories reviewed whenever possible. The remaining gaps were to be filled by means of a bottom-up approach, a study of patterns in expert teacher sequencing.

Chapter 4 focused on solutions that could satisfy the requirements of tailored rationales and structure-relatedness. Observed lawfulness in expert teacher sequencing was the basis for a model for structure-related sequencing. Chapter 5 describes the design of a learning environment that was based on this model. The design of this environment was strongly guided by the requirement to provide a form of non-directive support. Chapter 6, finally, describes an experimental study on the effects of the support provided by this learning environment.

# Toward prescriptions: a bottom-up approach 4

## 4.1 Introduction

In chapter 2 we adopted a top-down approach to obtain an answer to the question of how to support information space exploration. From a review of descriptive theory concerning sequencing, several requirements for fruitful exploration emerged. Prescriptive theory, as reviewed in chapter 3, could only partially provide design constructs[1] and prescriptions that satisfied these requirements.

Many of the prescriptive theories reviewed were so-called first generation instructional design theories. First generation theory is relatively coarse-grained in nature. Such theory provides a small number of general principles that are geared toward use by human instructional designers. In first generation design, the trend was one of parsimony in procedures. As such, most theories addressed the, probably most important, requirement in design for sequencing only, that of connecting to prior knowledge. Other aspects that were thought to be relevant for beneficial sequencing (chapter 2) were at least underexposed.

In this work, we did not aim at constructing a prescriptive approach for human instructional designers. The intention was to come up with design constructs and prescriptions for computer supported design. Systems for such support in the field of instructional design are commonly known as authoring systems. The design of exploratory learning environments aimed at in this thesis should be supported by authoring systems that are based on a prescriptive model. To form the core of such an authoring system, a prescriptive model could, and should be finer grained. We thus aimed at providing a second generation prescriptive model.

This model should address as many of the requirements as listed in chapter 2 as possible. Prescriptions for connecting to prior knowledge have been provided in currently available prescriptive theory. In consequence, we were to search for prescriptions that complied with the remaining requirements of *tailored rationales*, *structure-relatedness*, and *non-directiveness* of support.

In the study reported in this chapter we have made an attempt to come up with prescriptions that would satisfy the requirements of *tailored rationales* and *structure-relatedness*. In chapter 5 the requirement of *non-directiveness* of support will be tackled. In the present chapter, to get to prescriptions, we have adopted a bottom-up approach. From an analysis of sequences produced by experienced authors, we expected to gain insight into rationales applied in various domains and in the nature of the sequences imposed on the ordering structure.

[1] We will use the term 'design constructs' throughout this thesis to indicate constructs that are referred to in the prescriptions of a theory. Advance overviews, a meaningful layout, and iterative cumulation are examples of such design constructs.

## 4.2 Issues

**Tailored rationales** In chapter 2 we argued that the choice of rationale should be tailored to the target structure, or to learning-related aspects of the target structure. For example, if a learning task demands an understanding of a topological structure, that topological structure should, if possible, act as rationale, or, if the elements of the target structure strongly vary in complexity, then that target structure should be sequenced from simple to complex.

We formulated this idea as the requirement of *tailored rationales*. As this requirement was entirely based on theoretical considerations, we found it necessary to investigate whether it complied with current practice. We thus addressed the question of whether experienced authors would tailor rationale choice to the target structure(s), or whether they would, for instance, apply only a very restricted repertoire of rationales as was done in the majority of the prescriptive theories reviewed in chapter 3.

An investigation of sequences constructed by experienced authors should thus provide insight into the connection between target structure and rationale choice. We thus were to study what rationales could be found for a given target structure. Only in the case of a one-to-one connection between target structure and rationale for a sufficiently varied set of target structures, we might conclude that the requirement of tailored rationales actually complies with current practice.

**Structure-relatedness** In chapter 2 too we stated that having selected a structure to act as rationale is not sufficient for knowing how to actually construct a sequence. In that chapter, we attempted to get to prescriptions for the construction of the actual sequence. However, we got no further than stating that sequence "should be closely related to the ordering structure". In other words, sequence should be *structure-related*.

As with the requirement of tailored rationales, that of structure-relatedness was based on theoretical considerations only. Hence, a goal of the present study was to find out whether sequences constructed by experienced authors could be perceived to be 'structure-related'. If this was the case, the study should lead to an operational description of such structure-related sequence. To this end, sequences based on a particular rationale were analyzed for the presence of patterns. Such patterns in sequencing could be a first step toward the type of prescriptions needed for computer based instructional design.

## 4.3 Posner and Strike's categories of 'rationales'

The issues described above were to be explored by an analysis of a variety of sequences produced by experienced authors, as reflected in written material. These sequences were interpreted in terms of ordering structure, or rationale. Ordering structure is that structure that is found as acting as a basis for the sequence. For example, a chronological sequence is a sequence where a temporal structure acts as rationale.

In chapter 2 a categorization of rationales by Posner and Strike (1976) was introduced. This categorization lists many structures that have been found to act as a rationale for sequencing decisions. For what it is worth, the authors claim (p. 667) that their relation categories "are well grounded in what have proven to be useful distinctions in epistemology". Moreover, "the plausibility of the categorization scheme was tested against both the organization of extant curricula and literature on sequencing" (same page). The scheme lacks prescriptive utility for instructional design in that it contains no guidelines about which types of rationales are most effective for which type of content. It is, however, certainly useful as an analytical tool for the investigation described in this chapter. In the study on written material that is described below, the categorization acts as an interpretation scheme.

The categorization contains five main categories:

- *World-related rationales* that refer to structures that reflect the organization of empirical phenomena.
- *Concept-related rationales* that refer to structures derived from conceptual systems.
- *Learning-related rationales* that refer to structures that reflect an awareness of how people learn and develop.
- *Inquiry-related rationales* that reflect an organization of content consistent with the way the knowledge originally has come about.
- *Utilization-related rationales* that indicate characteristics from the situation in which the subject matter is to be applied.

It would go too far to give a full description of all rationales (see Figure 4.1) that are listed by Posner and Strike. For this reason, only those rationales that we found in the analysis of written material are described. For a description of the remaining rationales, the reader is referred to Posner and Strike (1976, pages 672-681). In the following sections, elements from the original descriptions[2] of rationales by Posner and Strike are printed in italic.

### 4.3.1 World-related rationales

Sequences based on world-related rationales are those orderings that are based on relationships between phenomena as they exist in the world. That is, world-related structures reflect empirical relationships among events, people, or tangible things. Types of world related structure include among others: temporal, spatial, or topological structure, and structure reflecting differences with respect to physical attributes.

**Temporal** According to Posner and Strike (p. 673) *"a temporal relationship between content elements reflects an antecedent-consequent order between events or between outcomes of events."* From their description we infer that temporal structures include both causal relations and relations reflecting ideological influence.

Considering the examples provided by others in the field (see e.g., Slavenburg, 1977; Lodewijks, 1983), this definition is restricted. It excludes those structures that contain events that have no causal or influence relation, but are found only to succeed each other in time as, for instance, in a history curriculum. In addition, procedures might also be seen as temporal structures.

It might be useful not to treat the category of temporal rationales as a whole, as it is likely that, for instance, historical and causal structures be treated differently in instruction. A causal structure might be taught starting at the resulting phenomenon, followed by a discussion of more and more

[2] It was not always possible to extract a definition from the original text. Therefore, we have attempted to reconstruct definitions by combining elements from the text. For this reason, the fragments printed in italic are not exact quotations.

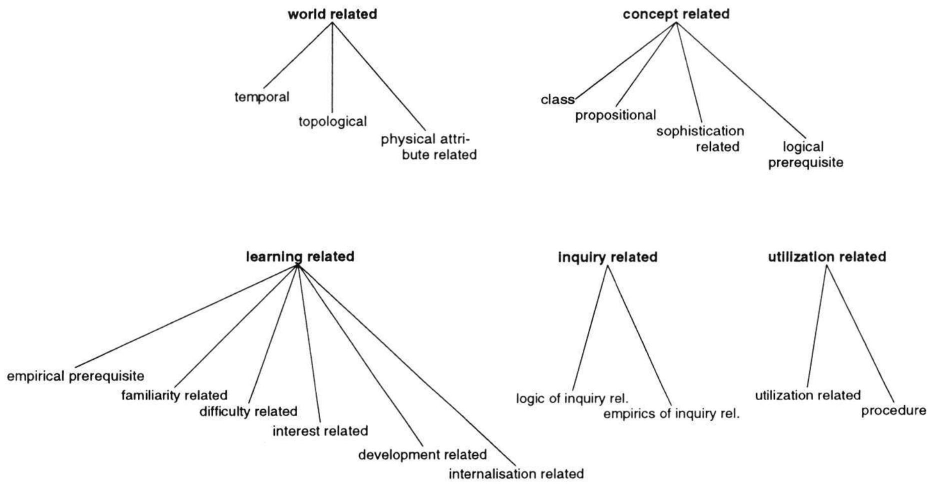



Figure 4.1: Rationales as originally presented by Posner and Strike (1976)

indirect causes, thus in a reverse chronological order (e.g., as was observed in the TIDES study[3] (Barnard *et al.*, 1992)). In contrast, historical structure is more likely to be treated in a chronological way (see e.g., Posner & Strike, 1976). In other words, different subtypes of temporal rationales may reveal different patterns in sequencing and more specifically, have different 'natural' directions.

In addition, in several instructional design theories (see e.g., Merrill, 1987) a distinction is made between the treatment of procedural ('internal' temporal) structure and historical ('external' temporal) structure. Procedural structure is characterized by a number of operations that are temporally related. Such procedural structure is labeled 'internal', as it is the learner who has to learn to perform the operations. External temporal structure is characterized by a number of (external) events such as might, for instance, be found in a history course. As both types of structures are found in abundance, both will be subject to analysis (section 4.8).

**Topological** Topological structure is defined to *"describe physical arrangements or position of entities"* (p. 672). *"Sequences based on a topological rationale include closest to farthest, top-to-bottom, left-to-right, west-to-east, etc"* (same page). Examples of topology-based sequences are: the discussion of language groups from west to east (as in Crystal, 1988[4]), the discussion of the learner's native country prior to neighbor countries and again prior to more remote countries (as e.g., in Allessie & van Mierlo, 1969).

It should be noted that frequently a procedural rationale is imposed upon material that is essentially topological in nature. Linde and Labov (1975), for instance, conducted an experiment

[3] In this study, a tutor explained a causal structure of phenomena leading to tidal elevation.

[4] All references to instructional material used in this study can be found in a separate reference list that is included Appendix A.1.

in which subjects were supposed to describe an apartment building. In their description, subjects consistently started at the entrance, circled round at the bottom floor, went one floor up, circled round and repeated this pattern until they had reached the toplevel. In their description, subjects thus 'wandered' through the building. The subjects thus imposed a procedural rationale upon an essentially topological structure. Similarly, left-to-right, west-to-east, top-to-bottom, north-to-south sequences can be assumed to be rooted in reading procedure (cf., Winn & Holliday, 1982). Although originally based on a procedural rationale, the sequences have become conventional for topological structures.

**Physical attribute related** A third type of world-related rationale is the physical attribute related which *is based on physical characteristics of the phenomena of interest, such as size, age, shape, number of sides, empirical complexity and countless other physical characteristics.* (p. 673). Sequences based on this rationale include, for example, increase in size, age, low to high empirical complexity. The discussion of the periodical system of elements in chemistry from low to high atom number is an example of a typical physical attribute related sequence.

### 4.3.2 Concept-related rationales

*"'Concept-related' structures are assumed to reflect the organization of the conceptual world, where 'world-related' structures are assumed to reflect the organization of the empirical world. In a conceptual world, concrete experiences, tangible things or substances are organized into categories"* (p. 673). For instructional purposes, sequences based on a concept-related rationale are frequently imposed on a domain. A conceptual organization, for instance, allows the construction of a general-to-specific sequence.

Posner and Strike mention four kinds of concept-related subtypes: hierarchical,[5] propositional, sophistication level, and logical prerequisite. Here, we will discuss the hierarchical rationale only, since this rationale was found in the written material used in this study.

**Hierarchical** A class concept is a concept *that groups a set of entities as instances of the same kind because they share common properties.* Typical hierarchical relations are, according to Posner and Strike, *inclusion (class-subclass), membership, union, intersection (part-of)* (p. 674).

With regard to hierarchical structures, Breuker et al. (1989) have made a distinction between generalization-specification structures and abstraction-concretion structures. Both types of structures may fit in the definition of hierarchical structures of Posner and Strike, however, in an analysis of sequences, it is a distinction that may not be neglected. Both types of structures may be sequenced entirely differently. The generalization-specification structure, for instance, acts as rationale in instructional design approaches such as the Elaboration theory (Reigeluth & Stein, 1983), the method of Progressive differentiation of (Ausubel, 1963) and Webteaching (Norman, 1973 described in (Tillema, 1983)). These theories prescribe a general-to-specific sequence. With respect to the second type of structure, the abstraction-concretion structure, prescriptions for both abstract-concrete and concrete-abstract sequences are found. Abstract-concrete sequences teach an abstract rule before illustrating this rule with instances from which the principle is derived. Examples can be found in the RULEG (RULe before EG(example)) work of Evans, Homme, and Glaser (1962).

[5]The category of hierarchical structures is originally named 'class-related', however, as the term 'hierarchical' is more conventional, we have traded the term class-related for hierarchical.

Concrete-abstract sequencing is applied in the EGRUL system (Markle, 1964, in Lodewijks, 1983). Here the student is confronted with a series of instances and is expected to formulate, or is confronted with, an abstraction only afterwards.

Finally, from the description of hierarchical relations we infer that also part-of structures are assumed to fall into the same category as the structures mentioned previously. This is, however, a somewhat unconventional standpoint. With Merrill (1983), we will make an explicit distinction between part-whole structures and class-related structures such as the generalization-specification, and abstraction-concretion structures, since it is anticipated that part-whole and class-related structures may be treated differently in instruction.

### 4.3.3 Learning-related rationales

The previous sections concentrated primarily on the nature of the target domain as a base for decisions on sequencing. However, many psychologists consider the nature of the domain less relevant to sequencing than notions about the way people learn. Where subject matter difficulty has been a main concern in deciding upon sequence, such a sequence is said to be based on a learning-related rationale. Learning-related rationales can, for instance, be the difficulty of the different subject matter elements, or the familiarity of elements to the student.

In the analysis of written material, frequently one can speculate only on the specific nature of a learning-related rationale. Whether a sequence is based on relative difficulty, or on familiarity, is usually hard to decide. In the analyses as described in this chapter, such a distinction could not be made beyond doubt. In consequence, we will discuss all categories of learning-related rationales.

**Empirical prerequisites** *"If it can be determined empirically that the learning of one skill facilitates or enables the acquisition of a subsequent skill, the first skill can be termed an empirical prerequisite of the second"* (p. 677).

An application of this rationale can be found in the cumulative learning theory as proposed by Gagné (1987). This theory prescribes that tasks be divided into elementary subtasks. These subtasks are taught in a cumulative way until all skills necessary for the target task are mastered.

**Familiarity** Past experiences of students are often used as the basis of sequencing. If this is the case, such a sequence is based on a familiarity-related rationale. *Familiarity refers to the frequency with which an individual has encountered an idea* (p. 678). In familiarity-based sequences, prior knowledge is used as a starting point and from here new knowledge is introduced gradually. This is usually done by organizing material in the form of a general-to-specific sequence, thus using a generalization-specification related rationale.

An example of a familiarity-based sequence is the presentation of the written material on oscillation as is discussed in chapter 7. All sources analyzed showed a similar starting point, a projection of circular motion on a vertical axe, to show the displacement-time graph so characteristic for oscillation. As circular motion had been treated prior to oscillation, a connection was laid from familiar material to new.

**Difficulty** Many factors may affect the subject matter's perceived difficulty. Posner and Strike name just a few: *"a) how fine a discrimination is required, b) how fast a procedure must be carried out, and c) the mental capacity required for learning"* (p. 678). Sequences based on a difficulty-related rationale teach the less difficult before the more difficult content.

**Anticipated interest** Interest is a factor which highly influences motivation and by that the effectiveness of instruction. *"Content elements that are intrinsically interesting are commonly those that refer to phenomena about which the learner has had some limited experience but that still remain a challenge. That is, retain the potential for surprise or can arouse curiosity"* (p. 678). Sequences based on an interest-related rationale usually try to connect to the learner's experiences in everyday life. That is, those elements that are most likely to provoke the learner's interest are presented first.

Along with the principle of connecting to prior knowledge, connecting to the learner's interests is one of the oldest principles for sequencing (Slavenburg, 1977).

**Development** Development-related rationales are applied *"to sequence content in a way that reflects the manner in which children develop psychologically"* (p. 679). In the Soviet psychology (see section 3.1.1), level of development has long been considered the most important rationale for subject matter organization. Sequences that deal with the level of development are mostly concentric sequences, where iteratively the same content is presented, each time at an anticipated next level in development (as in Bruner's (1966) Spiral curriculum).

### 4.3.4 Inquiry-related rationales

With inquiry-related rationales, *the process of generating, discovering or verifying (scientific) knowledge acts as a guideline for sequencing* (p. 676). Two types of inquiry-related rationales are distinguished. *If the sequence is related to 'the course of valid argument'*, it is said to be based on the *'logic' of inquiry*. Similarly, the *'empirics' of inquiry* can act as rationale. Here the sequence in which knowledge was originally acquired is replicated in the subject matter sequence. For example, in a case where successful researchers were found to study a large problem area before working on specific problems, subject matter could be sequenced so that it emphasizes the need for a general survey of an area prior to the consideration of specific problems.

### 4.3.5 Utilization-related

A final type of rationale is related to the anticipated use of acquired knowledge. Declarative content can be sequenced *in a way that reflects procedures for solving problems* where this declarative knowledge is applied (p. 680). In this case an *utilization-related* rationale is applied. An example of such a sequence was found in the material analyzed in the present chapter. In a text book of Minkenhof (1990) on criminal proceedings, various regulations with regard to warrants of arrest, discovery of evidence, litigation, punitive sanctions etc. were discussed in the (chronological) order in which these are relevant in a proceeding.

The difference with a procedural rationale (section 4.3.1) is that with a utilization-related rationale, it is declarative knowledge that is sequenced on the basis of a procedural rationale, whereas with a procedural rationale, procedural knowledge is sequenced where the procedural structure itself is used as rationale.

This category of rationales reveals that it is not always the target structure that directly acts as rationale. In this case a structure is imposed upon the target structure and is made to act as a rationale. For topological structures a similar phenomenon was observed, a procedural structure was imposed in order to linearize the inherently two-dimensional structure. With regard to the requirement of tailored rationales, this observation is relevant. It makes clear that it would be too easy to state that in all cases target structure should act as rationale.

A second type of utilization-related rationale is associated with the *anticipated frequency of use*. When applying this rationale, a course is organized so that the elements (mostly skills) that will be used most frequently, are taught first.

### 4.3.6 On the categorization scheme

Posner and Strike's scheme was based on study of actual instructional material and thus probably will be incomplete. More analyses of material, as, for example, in this chapter, may produce new rationales and new distinctions among rationales. Posner and Strike's scheme was used as a starting point for this study, since it is by far the most comprehensive scheme currently available.

## 4.4 Patterns in expert sequencing—an investigation

The main goal of this study was to find a connection between domain and rationale, and between rationale and sequence (section 4.2). The method used was to analyze existing written material and interpret it in terms of rationales applied. In this analysis of written material, Posner and Strike's categorization served as an interpretation scheme. It was used to interpret written material in terms of the rationales used.

The study of the written material was a two-stage exercise. It started with a pilot study that was highly exploratory in nature. This study yielded a tested instrument for reconstruction of sequences from written material and some initial hypotheses on patterns in sequencing. The second stage was an analysis of material covering specified rationales, with the intention of testing the hypotheses generated in the pilot.

## 4.5 Pilot study

### 4.5.1 Method

For a reconstruction of sequences from written material, a reconstruction of the underlying domain structure is a necessary first step. Such a reconstruction readily reveals which structures may have acted as rationale. Once a domain reconstruction had been made, the order in which elements from that domain structure are presented in the written material can be projected onto the domain structure. Analysis of the connection between structures that act as rationale and sequence is then straightforward.

A method was sought that enabled a reconstruction of the original domain structure. Initially, we constructed a highly advanced instrument for this reconstruction. This instrument provided a large selection of 'tactics', to be used for interpretation of written material. The set of tactics resulted from an integration of the 'events of instruction' by Gagné (1988), the 'presentation forms' by Merrill (1983) and the 'strategy components' by Reigeluth and Stein (1983). The resulting set of tactics included elements such as summaries, synthesizers, analogies, topic presentations, and topic illustrations (see van der Hulst & de Jong, 1991).

The idea was that an abstract description of the material, in terms of tactics and the domain elements incorporated by those tactics, would serve a separation of core material from peripheral material. Core material incorporated the actual presentation of domain entities and relations. Peripheral material incorporated tactics that supported linkage to prior knowledge and synthesis, and finally remaining tactics that specifically aimed at, for instance, motivation. The core material only was used for a reconstruction of the domain structure.

### 4.5.2 Source material

**Connection between domain and rationale choice** A first goal was to find out whether a particular target structure inevitably leads to a particular rationale choice. This question resulted from the demand to study the validity of the notion of *tailored rationales* (see section 4.2). This lead to the question of which rationales could be found for a given domain. Hence, we chose to analyze several books from different backgrounds covering similar domain material. To this end, four texts on the same subject of 'validity' were analyzed (Allen & Yen, 1979; Meerling, 1984; Kidder, 1985; Crocker & Algina, 1986).[6] This domain of validity, as all domains of analysis, was selected on the basis of 'availability' of material (see also section 4.6.3). The texts were derived from books on statistics or methodology for the social sciences.

**Connection between rationale and sequence** A second goal was to find out whether we could find patterns in sequencing, possibly related to the various rationales. Therefore, we additionally analyzed a number of sources that applied the same kind of rationale while covering different types of domains. This investigation was triggered by the desire to obtain an operational description of *structure-related* sequence (see section 4.2).

Sources that covered the same, in this case hierarchical rationale, were (Lodewick, 1972) on historical themes in Dutch literature, (Raat *et al.*, 172) on topics in physics, (Nelkon & Parker, 1970) on various kinds of oscillatory motion, and (Hannay *et al.*, 1989) on the various forms of punctuation.

### 4.5.3 Results

**Connection between domain and rationale choice** First, the results of an analysis of the sequence of topics in the four texts on validity are described. The four texts revealed a near identical hierarchical, more specifically a generalization-specification domain structure (see Appendix A.1, Figure A.1). The most general concept was that of 'validity' with as major types, 'content validity', 'predictive or criterion-related validity' and 'construct validity'. Meerling and Kidder elaborated on construct validity only, Allen and Yen and Crocker and Algina elaborated on several of the major types of validity.

The way different authors sequenced the material was highly similar. The analyses consistently revealed that the hierarchy was used as rationale for a coarse-grained organization. A top-down (i.e., general-to-specific), depth-first sequence was imposed on this hierarchy.

Even more remarkable was the consistency with respect to sequence at a fine-grained level. This level is found within the layers of the hierarchy. Within the first layer, the concept of content validity was treated prior to predictive validity which was again treated prior to construct validity. Kidder provided some insight into the rationale behind this sequence. She remarks that content validity is 'easier' compared to the other types of validity since it does not involve any statistical processing. Construct validity is seen as the most difficult of the three as the notion of 'construct' is a difficult one for students to understand. We may infer that, at a fine-grained level, the rationale has

[6] All references to material used in the present study can be found in a separate material reference section at the end of Appendix A.1.

been a learning-related simple-complex structure and the sequence was, not surprisingly, a simple-to-complex one.

The analysis of the four texts on validity reveals a strong mutual agreement among authors. The authors chose and combined the same rationales, where an imposed generalization-specification structure consistently took categorical dominance as rationale over the learning-related simple-complex structure. Moreover, the authors imposed similar sequences upon those rationales. This remarkably strong agreement among authors may have resulted from copying one and the same example, although this is not too likely as sources were from a different origin (Dutch, British, and American). More likely is that 1) the nature of a domain dictated rationale choice and that 2) rationale choice dictated the nature of the sequence. Both hypotheses will be investigated in the main study (section 4.6). The second hypothesis also introduces the second question of the pilot.

**Connection between rationale and sequence** To investigate the idea that rationale might dictate the nature of the sequence, we studied sequence in four texts covering different domains (themes in Dutch literature, concepts in physics, kinds of oscillatory motion, and forms of punctuation) that all applied a generalization-specification related rationale. All four texts described a hierarchy of about 3 or 4 levels deep, where the root concept was not much more than a 'place-holder'. With regard to patterns in sequencing, top-down and, no less consistent, depth-first sequences were found in all four texts.

Yet another observation was made. It was noticed that steps in a sequence, also named 'traverses', frequently seemed to be to directly related topics. High incidence of traverses that only bridge very short distance indicates a tendency of experienced authors to traverse only to directly related topics, that is, to *remain connective*. About 80% of the traverses bridged a very short distance. In the remaining 20%, several traverses were found that were from a leaf of a tree back up to reach a new branch of that tree. In these cases, it was thus inevitable to traverse a longer distance.

This tendency towards traversing short distances was never explicitly indicated in the prescriptive theories reviewed in chapter 2 as being important. Still, such a tendency might indicate an instructional design decision evident, maybe trivial, to human authors. Yet, to provide a foundation for automated support for authoring, such apparently trivial tendencies should be made explicit.

### 4.5.4 Conclusions

Three hypotheses emerged from the pilot:

- **The nature of the domain dictates rationale choice** In the pilot, the rationale choices for subject matter covering a similar domain were fully consistent. A next step was to investigate whether this connection between domain and rationale holds in general.

- **Patterns in sequences**

  - **'Natural' direction** In chapter 2 a relation between rationale and sequence was hypothesised. More specifically, it was argued that some rationales might have an associated 'natural direction'. Where hierarchical rationales were concerned, the pilot results supported this hypothesis. In the main study it should be investigated whether the hypothesis on natural direction also holds for other rationales.

- **Connectivity** In the pilot it was noticed that authors systematically tended to keep the distance covered by traverses as small as possible. They tried to keep traverses as 'connective' as possible. It should be studied whether this behavior is consistent for structures other than hierarchical ones.

## 4.6 Main study: patterns in expert sequencing

The pilot was intended to provide some first insights in the connection between domain structure and rationale choice, and that between rationale and sequence. The pilot study gave rise to hypotheses on the nature of these connections. In addition, it revealed a pattern in sequencing that was named 'connectivity'. This tendency to keep the distance covered by traverses as small as possible was not associated to a particular rationale, it was observed irrespective of the rationales applied. The hypotheses resulting from the pilot study, thus including the one on connectivity, were subject to investigation in the present study.

### 4.6.1 Method

In the pilot, domains were reconstructed in an indirect manner. Via a description of the material in terms of the tactics used, core material was filtered. From the core material a domain structure was reconstructed.

The conclusion after this pilot test was that a description in terms of tactics (see section 4.5.1) yielded a spectacular amount of information on instructional design, of which, however, only a relatively minor part was useful for a reconstruction of the domain structure. In the analysis of the material used in the pilot, it was noticed that the core material was reasonably well reflected in the section headings combined with typographical markers.[7] It was, therefore, decided no longer to use plain text as source material for analysis, but to go one level up and use the section organization, complemented with typographical markers in the text. It was now assumed that this level directly represented the core material and, therefore, the analysis in terms of tactics was abandoned.

The material was now analyzed in terms of the topics, or *entities*, and the *relations* between entities. It should be noted that it was not always clear from the section headers and typographical markers only what the nature of the relations was. We were thus obliged to descend incidentally to the textual level to retrieve information on the nature of relations.

Once a domain structure had been reconstructed, a trajectory that reflected the sequence in which elements from the structure were presented, could straightforwardly be projected onto this structure.

A final step was to analyze the sequences in terms of the patterns that were hypothesized earlier. That is, in terms of direction preference and connectivity. In the following sections, the methods of analysis of these patterns will be described.

**Reliability analysis** To assess the reliability of the method of domain reconstruction, a selection from both sets of material used in the main study were subjected to the same method of analysis by a second judge. From each set of 4 sources, one source was randomly selected. Thus, in total about 25% of the material was subjected to a second analysis. The percentage overlap of the second judge's reconstruction of the domain structures with that of the first judge was near to 90%.

[7]Typographical markers generally use a different font to indicate that certain text fragments have a special status.

### 4.6.2 Data Collection

#### 4.6.2.1 Direction preference

A measure for direction preference should yield insight into direction choice within a single 'ordering structure'. For the analysis of direction preference, the sequence imposed upon each ordering structure was described in terms of a pattern of forward and backward traverses.

For each relation $X \rightarrow Y$, a forward[8] traverse was assessed if entity $X$ was visited before entity $Y$. Conversely, if $Y$ was visited before $X$, a backward traverse was assessed. Some entities were visited more than once, in that case only the first time visit was taken into consideration. If $X$ or $Y$ was never visited, no traverse could be assessed.

The resulting trajectory description in terms of forward and backward traverses was judged against a norm for direction preference. Such a norm is a statement of the number of forward, or backward, traverses that would be minimally required to accept the pattern as evidently showing a forward or backward direction preference. This norm was named the norm for 'consistency of direction'.

The norm for consistency was obtained by using a binomial distribution to calculate the probability of the actual outcome under the assumption that no direction preference existed. If no direction preference would exists, the probability of a single forward or backward traverse would be .5, under the assumption that the number of missing traverses was negligible.

If the probability of absence of a direction preference, given the observed number of forward traverses ($x$) in a pattern, was calculated to be less than .05 (i.e., $P_{(\text{Number of forward traverses} \geq x)} < .05$), the pattern was taken to reveal a forward direction. In a similar way, a norm was defined for backward patterns.

#### 4.6.2.2 Connectivity

Connectivity was described as a tendency to 'traverse' only to directly related entities. A traverse represents a shift to a next entity. The distance $d$ of a traverse was determined by means of calculating the distance covered to get from entity $A$ to a the next entity in the sequence, entity $B$. The distance between entities $A$ and $B$ was defined as the number of relations of the domain structure to be traversed to get from $A$ to $B$ via the shortest path.

Occasionally, a large distance had to be covered to arrive at entities not yet visited. This is the case, for instance, if one ends in the leaves of a fully explored branch of a tree and has to return all the way back up to arrive at a new branch (see section 4.5.3). The distance measure was corrected for those situations. The 'unbiased' distance was calculated by having only relations to entities not yet visited add to the total distance. The mean unbiased distance $d$ of traverses within a text is an indication for the connectivity of exploration. The measure for *unbiased connectivity* was therefore defined as $\frac{1}{d}$.

**On the analysis** It should be noted that it was not in all cases possible to assess patterns in sequencing in an objective manner. Most domains subjected to analysis had an organization where there could be little doubt on the nature of the domain structure. For example, for a history course that discussed events in 1500, 1600, and 1700 respectively, a reconstruction would not lead to any

[8]Traverse direction was defined relative to the direction of a relation (i.e., a directed graph). In a tree, for example, all relations are defined to point toward the root, a traverse from the root one layer down is therefore classified as a *backward traverse*.

other structure than a temporal one, starting with events in 1500, and ending with events in 1700. However, whereas temporal organization is defined in an objective manner, we faced the lack of an objective definition of other structures, such as structures reflecting differences in empirical complexity and learning related difficulty.

In, for instance, texts on biological classification, all authors seemed to have adopted an 'empirical-complexity' structure as rationale. However, empirical complexity in this domain is a fuzzy notion and it is therefore difficult to judge whether a particular sequence deviates from such rationale. For example, two authors were found to discuss the class of 'viruses' as one of the first topics in the main class of micro organisms, yet a third author discussed the class of viruses almost at the end of the group of micro organisms (see Figure 4.2 in Appendix A.1). The question is, did this third author deviate from an empirical complexity-related sequence, or is discussion possible on the locus of the organism on an empirical complexity dimension? The latter appears to be the case. Along the empirical complexity dimension, organisms vary not only from single cell to multiple cell organisms, concurrently their reproductive, respiratory, circulation, digestive, excretion, and support function may get increasingly complex. In consequence, it may not be just to conclude that the author that discussed the class of viruses at the end of the micro organism group deviated from a simple-to-complex order. Empirical complexity in this case depends on the viewpoint the author might have adopted.

For structures that lacked an objective definition, a purely pragmatic solution was to take the majority's organization as the 'norm' organization.[9] In Figure 4.2 a fragment from the analysis of the four texts covering biological classification is given. The grey bar at the bottom of this figure provides a 'norm' for relative empirical complexity, where the less complex species are depicted left from the more complex ones.

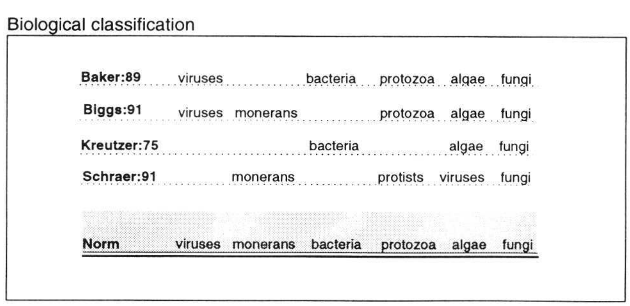



Figure 4.2: A fragment from the analyses of four sources on biological classification

In summary, it was not in all cases possible to assess patterns in sequencing in an objective manner. Consequently, a method to define an objective norm for structure was proposed. This method carries the danger that analysis of patterns in sequence is biased. To allow the reader to assess the seriousness of this bias, Appendix A.1 provides the reconstructions of and norm for those structures where the lack of an objective definition of structure played a role. All in all, the results provided in the following sections must be interpreted with this remark in mind.

[9] It is certainly no ideal solution as it assumes order of presentation as a direct reflection of the locus of entities on a structure. It should be remembered that the original question was whether the locus of entities on a structure was reflected in the order of presentation. The analyses made in the pilot, however, indicate that it is not unjust to assume that the order of presentation generally reflects the locus of entities on a structure.

### 4.6.3 Source material

For this study we again used written instructional material as a source. The material was selected on the basis of the following criteria:

- A text should clearly reveal one of the rationales mentioned by Posner and Strike.
- The selection of texts should be diverse with regard to target group and origin.
- For the study of the connection between domain and rationale choice, at least four texts should be available that covered the same domain.
- For the study of the connection between rationale and sequence, at least four texts should be available that covered the same rationale.

The selection of the source material was determined by availability in the collections of the library of educational material at Utah State University, a similar library at the University of Twente and the general library of the city of Amsterdam. No decision was made in advance on the rationales to be studied, therefore, rationales that were most frequently found (i.e., at least four times), were selected.

## 4.7 Similar domain material study

To investigate the hypothesis on the connection between domain and rationale choice, sets of *various texts* covering a *similar domain* were analyzed. The major issue was whether rationale choice would vary among these texts. If all sources revealed a similar rationale choice, a secondary issue was whether patterns in sequencing could be observed.

### 4.7.1 Source material

Subject matter covering the following domains was analyzed:

- **Kinematics** Material on kinematics that covered part of the curriculum for classical mechanics for high school or undergraduate level. High level concepts were *linear* and *non-linear motion*, *collision*, *oscillation*, and *waves*.
- **Biological classification** Material that provided an account of taxonomy in biology for high school, junior or senior level. The classification of organisms in biology covered general concepts such as 'micro organisms', 'plants', 'invertebrates', and 'vertebrates', while the bottom levels included specific classes of organisms such as 'sponges', 'insects', 'amphibians'.
- **Occupational groups** Material covering a discussion of occupational groups, such as 'agriculture', 'industry' and 'commerce', in material on geography. The target groups varied from children in elementary education to adults.

Table 4.1 lists the sources used in the analysis, with reference to their intended *target group* and *origin*. The *code* in the second column is used in the results section to refer to the particular source.

Table 4.1: Sources in the similar domain material study

| *Domain* | *Code* | *Reference* | *Target group* | *Origin* |
|---|---|---|---|---|
| *Kinematics* | | | | |
| | Middelink:78/79 | (Middelink, 1978, 1979) | senior high | Dutch |
| | Schweers:70 | (Schweers & van Vianen, 1970) | senior high | Dutch |
| | Alonso:78 | (Alonso & Finn, 1978) | undergraduate | American |
| | Nelkon:70 | (Nelkon & Parker, 1970) | undergraduate | British |
| *Biological classification* | | | | |
| | Baker:91 | (Baker *et al.*, 1991) | senior high | American |
| | Biggs:91 | (Biggs et al., 1991) | senior high | American |
| | Kreutzer:75 | (Kreutzer & Oskamp, 1975) | junior high | Dutch |
| | Schraer:91 | (Schraer & Stoltze, 1991) | junior high | American |
| *Occupational groups* | | | | |
| | vanDongen:83 | (Van Dongen *et al.*, 1983) | elementary ed. | Dutch |
| | deBoer:83 | (de Boer *et al.*, 1983) | elementary ed. | Dutch |
| | Allesie:69 | (Allessie & van Mierlo, 1969) | senior high | Dutch |
| | Zuelen:85 | (Zuelen *et al.*, 1985) | adult ed. | Dutch |

Three sets of material, each set including four texts covering a similar domain, were subjected to analysis. The question to be answered on the basis of these sets was whether, when covering a similar domain, rationale choice was consistent among texts.

In Appendix A.1 the domain reconstructions can be found of the texts covering the domains of kinematics, biological classification, and occupational groups. From these reconstructions it can be observed that the domain structures reveal many similarities. Where differences are found, these are mainly in the elaborateness of the material.

Alongside each reconstruction of domain structure, the order of presentation of the subject matter in each set is outlined. The four texts are presented so that similar parts are presented together. By this, it can easily be seen where differences among texts can be found. Associated to the reconstructions, a 'norm sequence' is depicted that reflects the sequence by the majority. With such a norm, data on direction preference and connectivity could be calculated.

### 4.7.2 Results

In the following paragraphs, for the three types of domains, rationale choice and the direction imposed on those rationales will be discussed.

#### 4.7.2.1 Kinematics

**Rationale** All sources were observed to have combined a generalization-specification rationale with a learning-related difficulty rationale. The structure that reflected learning-related difficulty could be found within the layers of the hierarchical generalization-specification structure (see Figure A.3 in Appendix A.1).

High level concepts were 'linear' and 'non-linear motion', 'collision', 'oscillation', and 'waves'. The leaves of the hierarchy incorporated concepts such as 'horizontal throw' and 'motion under gravity'. With respect to the simple-complex structure, generally, the concept of 'uniform motion in a straight line' was regarded as the most simple, followed by uniformly accelerated motion, followed by non uniformly accelerated motion.

**Direction** The elements of the generalization-specification structure were consistently presented in a general-to-specific order and the learning-related difficulty structure from simple-to-complex (see Table 4.2).

The Tables 4.2, 4.3, and 4.4 provide data on rationale choice and on direction preference. These tables show: 1) the *rationale choice*, 2) the number of *forward* and *backward* traverses observed. Finally, 3) the column labeled *Consistency?* provides an answer to the question of whether the pattern observed reveals consistency in direction choice and if so, in which direction. The calculation of a norm for consistency was explained in section 4.6.2.1.

For branched structures, the notions of backward and forward are translated to 'top-down' and 'bottom-up' respectively. Generalization-specification structures are in all tables abbreviated to 'gen-spec'. Finally in Table 4.2, learning-related difficulty is put in short form as 'difficulty', and 'forward' direction is translated into the more meaningful 'simple-to-complex' direction.

Table 4.2: Rationale choice and direction preference in material on kinematics

| *Source* | *Rationale choice* | *Forward* | *Backward* | *Consistency?* |
|---|---|---|---|---|
| Middelink:78/79 | gen-spec | | 15 | top-down |
| Schweers:70 | gen-spec | | 13 | top-down |
| Alonso:78 | gen-spec | | 8 | top-down |
| Nelkon:70 | gen-spec | | 13 | top-down |
| Middelink:78/79 | difficulty | 13 | | simple-to-complex |
| Schweers:70 | difficulty | 9 | 1 | simple-to-complex |
| Alonso:78 | difficulty | 11 | | simple-to-complex |
| Nelkon:70 | difficulty | 11 | | simple-to-complex |

#### 4.7.2.2 Biological classification

**Rationale** Again, substantial consistency with respect to rationale choice was observed (see Figure A.5 in Appendix A.1). All sources combined a generalization-specification rationale with an empirical-complexity rationale. Concepts in the top of the generalization-specification structure were, 'micro organisms', 'plants', 'invertebrates', and 'vertebrates', while the bottom levels included topics such as 'sponges', 'insects', 'amphibians'. The empirical complexity structure revealed an evolution from 'single cell organisms' to highly complex organisms such as 'mammals'.

**Direction** The generalization-specification structures were presented consistently in a top-down (backward) direction, and the empirical complexity structure from simple to complex (i.e., a forward direction) (see Table 4.3).

#### 4.7.2.3 Occupational groups

**Rationale** Within the material on occupation groups, two types of organizations were found. Two sources combined a generalization-specification rationale with a familiarity-related rationale. The

Table 4.3: Rationale choice and direction preference in material on biological classification

| *Source* | *Rationale choice* | *Forward* | *Backward* | *Consistency?* |
|---|---|---|---|---|
| Baker:91 | gen-spec | | 18 | top-down |
| Biggs:91 | gen-spec | | 18 | top-down |
| Kreutzer:75 | gen-spec | | 19 | top-down |
| Schraer:91 | gen-spec | | 17 | top-down |
| | | | | |
| Baker:91 | empirical complexity | 17 | | simple-to-complex |
| Biggs:91 | empirical complexity | 15 | | simple-to-complex |
| Kreutzer:75 | empirical complexity | 15 | 2 | simple-to-complex |
| Schraer:91 | empirical complexity | 13 | 1 | simple-to-complex |

other two sources applied a familiarity-related rationale only (see Figure A.7 in Appendix A.1). The familiarity-related ordering structure listed occupational groups starting with the primary sector, 'agriculture', then from 'industry', to 'commerce' (in some case 'transport'), to the tertiary sector, the 'service industry'.

**Direction** The elements of the familiarity-related structure were sequenced from primary to higher order sectors (see also Table 4.4). This sequence was interpreted as a familiar-to-unfamiliar sequence.

Table 4.4: Rationale choice and direction preference in material on occupational groups

| *Source* | *Rationale choice* | *Forward* | *Backward* | *Consistency?* |
|---|---|---|---|---|
| vanDongen:83 | familiarity-related | 5 | | familiar-to-unfamiliar |
| deBoer:83 | familiarity-related | 4 | | familiar-to-unfamiliar[α] |
| Allesie:69 | familiarity-related | 6 | | familiar-to-unfamiliar |
| Zuelen:85 | familiarity-related | 4 | 1 | |
| | | | | |
| vanDongen:83 | gen-spec | 6 | | top-down |
| Allesie:69 | gen-spec | 6 | | top-down |

[α] Indicates a forward direction at $\alpha = .06$

### 4.7.2.4 Connectivity

The analysis of connectivity of the similar domain material revealed substantial connectivity, irrespective of domain or rationale choice. That is, in the material reviewed, almost all traverses were to directly related topics.

Table 4.5 provides data on the nature of rationales found in the material *(Rationale choice)*, the number of traverses within a structure *(n)* and the unbiased connectivity of these traverses *(Conn)*. The data on connectivity can be compared with a *Base rate* for connectivity. This base rate is the connectivity rating that would be acquired for randomly traversing through the particular domain structure. The base rate is obtained by calculating the mean unbiased connectivity of 100 randomly generated sequences within the particular domain structure.

Table 4.5: Unbiased connectivity

| *Source* | *Rationale choice* | *n* | *Conn.*[α] | *Base rate* |
|---|---|---|---|---|
| Middelink:78/79 | gen-spec/difficulty | 20 | 1 | .43 |
| Schweers:70 | gen-spec/difficulty | 17 | .94 | .42 |
| Alonso:78 | gen-spec/difficulty | 13 | 1 | .54 |
| Nelkon:70 | gen-spec/difficulty | 19 | 1 | .43 |
| Baker:91 | gen-spec/empirical complexity | 18 | 1 | .57 |
| Biggs:91 | gen-spec/empirical complexity | 18 | 1 | .55 |
| Kreutzer:75 | gen-spec/empirical complexity | 20 | .91 | .54 |
| Schraer:91 | gen-spec/empirical complexity | 17 | .94 | .50 |
| vanDongen:83 | gen-spec/familiarity-related | 11 | 1 | .54 |
| deBoer:83 | familiarity-related | 4 | 1 | .75 |
| Allesie:69 | gen-spec/familiarity-related | 11 | 1 | .55 |
| Zuelen:85 | familiarity-related | 4 | .57 | .66 |

[α] Connectivity was determined for each complete structure, irrespective of whether it was composed of more than one primitive structure.

The average connectivity for the above listed 12 sources is .95 ($SD = .13$) where the average connectivity based on randomly traversing (the base rate) is .54 ($SD = .10$). This difference is significant (two tailed t-test, $t = 7.9$, $df = 11$, $p < .00$). The connectivity of the authors' traversing is thus substantially higher than might be expected on the basis of random traversing.

## 4.8 Similar rationale material study

It was hypothesized in section 4.4 that some rationales might have an associated 'natural direction'. The analysis based on the 'similar domain' material supported this hypothesis. Except for the data on direction for the material of *Zuelen:85* on occupational groups, all outcomes are consistent with respect to direction for a specified rationale type. For instance, the 10 times a generalization-specification ordering structure was found, for each of a top-down sequence was imposed on this structure. An empirical complexity rationale was found 4 times, in all cases a forward direction preference is observed.

However, to be able to make a statement on the validity of the hypothesis that some 'rationales have an associated natural direction', the similar domain material is not suitable. A connection between rationale and direction preference within similar domain material is one thing, finding such a connection within varying domain material is something completely different.

#### 4.8.0.5 Source material

Analysis of a second set of material, covering *various domains* but *similar rationales*, should thus provide an answer to the question of the relation between rationale and direction. As in the previous study the same material was also used to assess connectivity of traversing.

The following source material was used:

- **Generalization-specification**
  - **Davidson:91:** on themes in American history
  - **Visser:70:** on themes in British and American literature
  - **Novem:78:** on the organization of Dutch authorities
  - **Kreutzer:75:** on a taxonomy of plants
- **Historical**
  - **Davidson:91:** on events in American history,
  - **Visser:70:** on British and American literature, organized by date of birth of the discussed authors
  - **Novem:78:** on the growth of European civilizations, organized by events of importance,
  - **Faber:48:** on geology of the Netherlands, organized by period of origin of geological structures
- **Procedural**
  - **Minkenhof:90:** on criminal proceedings in the Netherlands, organized by utilization procedure (see section 4.3.5)
  - **Briggs:91:** on instructional design procedures
  - **Stevens:78:** on first aid procedures
  - **Talaico:82:** on behavioral objectives for habilitation, organized by utilization procedure
- **Topological**
  - **Crystal:88a:** on Creol languages, organized by geography of incidence
  - **Crystal:88b:** on Indo-European language varieties, organized by location of incidence
  - **Faber:47:** on the geology of the Netherlands, organized by region
  - **Heldring:90:** on the geography of Indonesia
  - **Broos:91:** on a discussion of sport injuries, organized by anatomy

Again, the sources used in this analysis are listed in Table 4.6, with reference to their intended target group and origin.

### 4.8.1 Results

#### 4.8.1.1 Rationale and direction preference

**Generalization-Specification rationale** For generalization-specification ordering structure, the data reveals a persistent preference for a top-down (i.e., backward) direction, see Table 4.7.

Table 4.6: Sources in the similar rationale material study

| *Rationale* | *Code* | *Reference* | *Target group* | *Origin* |
|---|---|---|---|---|
| *Generalization-specification* | | | | |
| | Davidson:91a | (Davidson & Batchelor, 1991) | junior high | American |
| | Visser:70a | (Visser, 1970) | senior high | Dutch |
| | Novem:78 | (Novem (pseud.)., 1978) | senior high | Dutch |
| | Kreutzer:75a | (Kreutzer & Oskamp, 1975) | junior high | Dutch |
| *Historical* | | | | |
| | Davidson:91b | (Davidson & Batchelor, 1991) | junior high | American |
| | Visser:70b | (Visser, 1970) | senior high | Dutch |
| | Novem:78 | (Novem (pseud.)., 1978) | senior high | Dutch |
| | Faber:48 | (Faber, 1948) | senior high | Dutch |
| *Procedural* | | | | |
| | Minkenhof:90 | (Minkenhof, 1990) | university | Dutch |
| | Briggs:91 | (Briggs *et al.*, 1991) | university | American |
| | Stevens:78 | (Stevens *et al.*, 1978) | elementary ed. | American |
| | Talaico:82 | (Talaico & Hewit Slusher, 1982) | mentally hand. | American |
| *Topological* | | | | |
| | Crystal:88 | (Crystal, 1988) | university | American |
| | Faber:47 | (Faber, 1947) | senior high | Dutch |
| | Heldring:90 | (Heldring, 1990) | adult ed. | Dutch |
| | Broos:91 | (Broos, 1991) | higher voc. ed. | Dutch |

Table 4.7: Direction preference associated with a generalization-specification rationale

| *Source* | *Rationale choice* | *Forward* | *Backward* | *Consistency?* |
|---|---|---|---|---|
| Davidson:91a | gen-spec | | 40 | top-down |
| Visser:70a | gen-spec | | 138 | top-down |
| Versteeg:90a | gen-spec | | 24 | top-down |
| Kreutzer:75a | gen-spec | | 53 | top-down |

**Historical and procedural rationales** As discussed in section 4.3.1, in several instructional design theories a distinction is made between the treatment of procedural ('internal' temporal) structure and historical ('external' temporal) structure. Procedural structure was characterized by a series of operations that are temporally related. Such temporal structure was labeled 'internal' as it is the learner who has to learn to perform the operations. Historical structure was characterized by a series of (external) events, as can be found in a history course.

As Table 4.8 shows, both types of structures are associated with a strong forward, thus, chronological direction preference. The chronological direction preference is consistent for all material analyzed.

**Topological rationales** Two types of topological rationales were selected, namely relations that define a relative position on a horizontal dimension and one on a vertical dimension.

The results on direction preference associated with topological structure (Table 4.9) are less consistent than the results obtained for the previously discussed rationale types. Three out of four horizontal structures reveal a left-to-right (i.e., forward) direction preference and two out of four

Table 4.8: Direction preference associated with temporal and procedural rationales

| *Source* | *Rationale choice* | *Forward* | *Backward* | *Consistency?* |
|---|---|---|---|---|
| Davidson:91b | historical | 20 | | chronological |
| Visser:70b | historical | 99 | 2 | chronological |
| Novem:78 | historical | 5 | | chronological |
| Faber:48 | historical | 9 | | chronological |
| Minkenhof:90 | procedural | 9 | | chronological |
| Briggs:91 | procedural | 6 | | chronological |
| Stevens:78 | procedural | 55 | | chronological |
| Talaico:82 | procedural | 22 | | chronological |

vertical structures reveal a top-to-bottom (i.e., forward) direction preference.

In *Crystal:88a*, *Crystal:88b* and *Faber:47* both horizontal and vertical structures are present in a single domain representation. In all cases, one of the structures is found to be categorically dominant. In *Crystal:88a* and *Crystal:88b* the horizontal dimension is dominant, in *Faber:47* the vertical dimension. This distinction leads to an important observation: all non-dominant structures fail to reveal a direction preference. In contrast, all other structures do reveal a direction preference. To explain this effect, it should be noted that it is almost impossible to traverse a two dimensional space both consistently left-to-right and top-to-bottom.

Table 4.9: Direction preference associated with topological rationales

| *Source* | *Rationale choice* | *Forward* | *Backward* | *Consistency?* |
|---|---|---|---|---|
| Crystal:88a | topol.(horizontal) | 59 | 18 | left-to-right |
| Crystal:88b | topol.(horizontal) | 6 | | left-to-right |
| Faber:47 | topol.(horizontal) | 3 | 2 | |
| Heldring:90 | topol.(horizontal) | 5 | | left-to-right |
| Crystal:88a | topol.(vertical) | 41 | 29 | |
| Crystal:88b | topol.(vertical) | 3 | 2 | |
| Faber:47 | topol.(vertical) | 9 | | top-to-bottom |
| Broos:91 | topol.(vertical) | 7 | 1 | top-to-bottom |

#### 4.8.1.2 Connectivity

The analysis of unbiased connectivity within the 'similar domain' study revealed substantial connectivity, irrespective of domain type or source, see Table 4.10. Because of the evident trend towards connectivity we perceived no need to calculate base ratings for connectivity as in section 4.7.2.4.

#### 4.8.1.3 Explorations

**Categorical dominance** The material on kinematics and biological classification and, in the pilot, the material on validity revealed an evident categorical dominance for a generalization-

Table 4.10: Connectivity

| *Source* | *Rationale choice(s)* | *n* | *Conn.* |
|---|---|---|---|
| Davidson:91 | gen-spec/historical | 40 | 1 |
| Visser:70 | gen-spec/historical | 138 | .94 |
| Versteeg:90 | gen-spec/historical | 25 | 1 |
| Baker:89 | gen-spec/emp.complexity | 18 | 1 |
| Kreutzer:75 | gen-spec/emp.complexity | 54 | 1 |
| Faber:48 | historical | 9 | 1 |
| Novem:78 | historical | 6 | 1 |
| Crystal:88a | topological | 87 | .89 |
| Crystal:88b | topological | 8 | 1 |
| Heldring:90 | topological | 5 | 1 |
| Faber:47 | topological | 13 | 1 |
| Broos:91 | topological | 8 | 1 |
| Minkenhof:90 | procedural | 9 | 1 |
| Briggs:91 | procedural | 6 | 1 |
| Stevens:78 | procedural | 55 | 1 |
| Talaico:82 | procedural | 22 | 1 |

specification rationale. In the similar domain material too, we frequently observed a coarse-grained generalization-specification organization with at a fine-grained level, an organization by means of other rationales. Exceptions can, for instance, be found in procedural matter where students are directly confronted with the full procedure, as, for instance, in *Stevens:78* and *Talaico:82*.

Other rationale combinations were found, as in the topological material horizontal and vertical rationales, but with no consistent categorical dominance for either of the rationales. Rationale choice appears to depend on the shape of the spatial structure of which elements are sequenced. For sequencing regions in the Netherlands, the Netherlands being a vertical elongated shape, a vertical rationale was used for coarse-grained organization. Conversely, for a discussion of language isolates from a horizontal projection of the globe, a horizontal coarse-grained organization was found.

**Structure form and direction preference** During the analysis, the idea emerged that direction might not only be dictated by the nature of the rationale but also by the form of the structure upon which the sequence was imposed. To explore this idea, we investigated structure form for each source. The results reveal that all branched structures were observed to have a top-down direction preference. It should be noted that all branched structures were of a similar kind, namely generalization-specification structures. The question is, what gave rise to the top-down direction preference found: the hierarchical nature of the relations in the structure, or the structure form. In the following chapter we will discuss the effect of structure form separately.

## 4.9 Conclusion

The investigation of the way in which authors of written material sequenced domains (see also van der Hulst, 1992) provided us with an insight into rationales used and patterns in sequences imposed.

### 4.9.1 Tailored rationales

A first hypothesis investigated in this study was: "The nature of the domain dictates rationale choice", as worded in the conclusion from the pilot study in section 4.5.4. With respect to the kinematics material and the biological classification material, indeed, full consistency in rationale choice was observed. In the material on occupational groups, the familiarity-related rationale was found consistently, however, two authors additionally imposed a generalization-specification structure upon the material and used this structure as rationale for a coarse-grained organization.

In our view, these results suggest a strong connection between domain and rationale. Each structure type might have an associated 'natural' rationale for sequencing. This was exactly what was implied in the 'tailored rationales' requirement.

As the repertoir of domain structures can be large, this finding suggests that authors use a large repertoir of rationales for sequencing. In contrast, the approaches as reviewed in chapter 3 were argued to be based on a very limited repertoir of rationales. Consequently, we have reasons to believe that the way in which experienced authors sequence material does not comply with those approaches. The single rationale-based approaches, as discussed in that chapter, may prescribe a too restricted approach.

**Categorical dominance and the combination of rationales** In the analysis in the 'similar domain' study it might be sound to make a distinction between two levels of organization. At a *coarse-grained level* of organization, we frequently found a generalization-specification rationale. This finding is in line with prevailing first generation instructional design theory that prescribed to impose a generalization-specification structure upon subject matter material and consequently to adopt this structure as rationale. It was argued in chapter 2 that a so resulting generalization-specification rationale-based organization supported connection to prior knowledge by implementing a form of *iterative cumulation*. For coarse-grained organization, a single rationale approach, as in the prescriptive theories of, for example, Ausubel and Reigeluth, is thus found to comply with current practice.

On the other hand, at a fine-grained level, each type of domain structure was found to be accompanied by a different type of rationale. For instance, classifications in biology are generally based on differences in empirical complexity, hence empirical complexity is important for a student to understand and it is therefore not surprising that for sequencing an empirical complexity-related rationale was found to be adopted. For the kinematics material, a learning-related rationale was evidently more suitable. It is assumed important for learners to understand notions such as uniform linear motion, before learning more complex notions in kinematics. As a result, in the kinematics material, sequence was dictated by a learning-related difficulty rationale. All in all, at a *fine-grained level* of organization, it was observed that domain structure and learning-related aspects of a particular domain were reflected in the choice of rationale. This is what was intended with the requirement of tailored rationales.

**Prescriptions** As we have adopted a knowledge engineering approach to the construction of a prescriptive model, patterns as observed in sequences by experienced authors are assumed to reflect an expert approach in sequencing. Consequently, these patterns are accepted as a basis for prescriptions. The observations listed above thus result in a first prescription:

- *For support for information space exploration a distinction should be made between coarse- and fine-grained organization.*

- *To support* **connection to prior knowledge** *by iterative cumulation, a generalization-specification structure is to be imposed upon the domain and be chosen to act as rationale for sequencing at a coarse-grained level.*
- *At a fine-grained level, domain and learning-related structures present must be reflected in the rationale choice.*

In chapter 5, an example is provided of an operationalization of the distinction between coarse and fine-grained organization.

An aspect in the prescription that must be made explicit is how domain aspects and learning-related aspects can be reflected in a sequence. With this we have arrived at the second question posed in this study, that of patterns in sequencing.

### 4.9.2 Structure-relatedness

The second and third hypotheses both concern the nature of sequences created by experienced authors. It is concluded that with only a few exceptions, experienced authors were found to be sequencing the instructional material in a highly methodical way.

Three patterns emerged, we will start with the pattern that was found in all material, irrespective of the nature of the domain and rationales applied:

- **Connectivity** The data on *connectivity* confirmed the hypothesis that authors of written material scrupulously tried to relate new material to material previously discussed. Often, traverses were made to directly related topics.
- **Consistency of direction** With respect to direction preference, the data on direction in general revealed a strong *consistency of direction* within a structure. That is, a direction once chosen was usually maintained.
- **'Natural direction'** For several rationales, the data on direction preference confirmed the idea that a connection exists between rationale (thus ordering structure) and direction in which the ordering structures were traversed. That is, some structures were found to have an associated *'natural' direction.*

  As a criterion for a connection between rationale and 'natural' direction we decided that at least three out of four sources in a set should reveal a similar direction. Hence, the data yielded evidence for the following combinations of rationale and 'natural' direction:

  - *Generalization-Specification* rationale, a *general-to-specific* direction;
  - *Historical* rationale, a *chronological* direction;
  - *Procedural* rationale, a *chronological* direction;
  - *Topological* horizontal rationale, a *left-to-right* direction.

In conclusion, expert sequence can be characterized by connectivity, consistency of direction and in some cases by the pursuing of a 'natural' direction. Such a sequence is closely related to the structure that acts as rationale. Hence, the sequence that reflects connectivity, consistency and 'natural' direction is labeled a **structure-related** sequence.

**Prescriptions** With this conclusion we have arrived at prescriptions. To guarantee that domain and learning-related structures are reflected in the sequence, this sequence should comply with the conventions of structure-related sequencing. Prescriptions for structure-related sequencing are defined as follows:

- **Connectivity** *The distance bridged by a traverse must be as small as possible.*
- **Consistency of direction** *When traversing a structure, a direction once chosen must be maintained throughout that structure.*
- **'Natural' direction** *If a natural direction is known for a structure, the traverses must follow that natural direction.*

### 4.9.3 SEQModel

The analysis in this chapter resulted in several prescriptions. These prescriptions form the core of a model for support for information space exploration. This model was named SEQModel. Chapter 5 describes the design of an authoring tool (SEQTool) that implements a form of support that is based on the prescriptions of SEQModel. The intention of this chapter was to provide a second generation prescriptive model. Such a model should be sufficiently specific and non ambiguous to be readily implementable in an authoring tool. The implementation of SEQTool should be a testcase to see whether this was indeed the case. Finally, in chapter 6 an experiment is described in which benefits of the support based on SEQModel were assessed.

## 4.10 Discussion

From a knowledge engineering perspective, a synthesis of the sequencing by experienced authors indicates to a certain extent 'good' educational practice. Statements on good educational practice have provided a basis for prescriptions for instructional design. A final step made here is a reflection upon the prescriptions for structure-relatedness in the light of ideas from related work, in this case that of linguistics and cognitive science.

### 4.10.1 Connectivity

**Analysis of written material** Free information space exploration allows students to 'jump' through the domain. That is, to traverse to indirectly related topics. In contrast, a conclusion we could draw from the study of sequences of experienced teachers was that those teachers scrupulously tried to avoid this 'jumping'. Instead of 'jumping' trough the material, teachers were found to choose a route so that each new topic would have at least some relation to the former. That is, they strived to attain *connectivity*.

**Linguistics** In the field of linguistics, a highly similar type of behavior is described. In discourse, each step, a shift of topic, is to a directly related one, as (Levelt, 1989, p. 110) remarks, "The defining characteristic of coherent discourse is that every move of a speaker is in some way related to whatever was said before". Listeners anticipate on this behavioral pattern and thus base their interpretation of a message on the assumption of relatedness. It is a tacit consent between speaker and addressee that says that a new topic is always directly related if not explicitly said otherwise. This consent is presented as one of the major 'conventions' in linguistics. The convention is named the 'maxim' of relevance (Grice, 1975), also known as the convention of 'connectivity' (Levelt, 1982; Levelt, 1989). Behavioral patterns such as that of 'connectivity' in linguistics are of major importance for efficiency in communication. Since both speaker and receiver know that a new topic has some relation to the previous one, this does not need to be made explicit. Hence, things can be left unsaid, making discourse more compact.

**Cognitive science** To understand the scope of a behavioral pattern it is essential to know whether the behavioral pattern is 'natural' in the sense that it is rooted in the limitations of the cognitive system or that the pattern is learned and thus may vary over cultures.

Considering the pattern of connectivity, from a cognitive point of view it may well be essential to acquire new subject matter in a connective way. A study by Bower (1969) provided evidence that connectivity leads to better recall. This study revealed that a set of 112 concepts ordered so that their inter-concept associations were evident was recalled far better than the same set of concepts presented in random order. The results of Bower et al. are explained in the following way (see Glass *et al.*, 1979): 1) Presumably the random order failed to reveal the multitude of associations between concepts. If this is true, connectivity makes associations between concepts more manifest. 2) The associative nature of memory made recall of a set of related concepts far easier than the recall of a similarly large set of less related concepts, since each concept recalled could act as a cue for the recall of related concepts as was, for instance, demonstrated by Jenkins and Russel (1952). The former indicates that for learners it might be beneficial to be confronted with new material in a connective way.

Now, does the speaker anticipate the learner's needs or is the connective ordering of material also 'natural' for a speaker? For speakers too, associative nature of memory might play a role in determining the order of topics to be discussed. It may be equally hard for a speaker to discuss a multitude of topics in a non connective way. For a speaker too, each topic may act as a cue for related topics and this allows discussing a subject without having recalled all topics in advance.

Discussing topics in a random order certainly makes bookkeeping laborious. That is, keeping track of what has been discussed and what still needs to be discussed. Levelt (1982), for instance, argues that the inherent limitations of working memory may demand connectivity. To keep the burden on working memory as small as possible, speakers will traverse a multidimensional structure in such a way that the amount of backtracking needed will be minimized and as he claims, this results in connectivity.

It is well possible that a speaker naturally discusses topics in a connective way due to limitations of associative and working memory. In addition, a speaker might foresee the potential difficulty of the addressee to remember the things said and may thus try to prestructure a chain of expressions so that processing is as easy as possible. Returning to the issue of scope, due to the assumed roots in the cognitive system, the convention of connectivity is likely to be universal.

In summary, analysis of written instructional material and discourse theory provide evidence that both authors and speakers aim at connectivity. Connectivity in discourse has the function of streamlining discourse. We have argued that the connectivity convention did not come out of the blue, but could well be a consequence of the constraints of the cognitive system. If this is true, deviation from a connectivity pattern may not be without consequences.

### 4.10.2 Consistency of direction

**Analysis of written material** A second conclusion from the study on experienced teacher sequencing was that teachers, besides organizing the material in a connective manner, also tended to continue in a direction once chosen. Once they had decided to describe a history domain in a chronological order, they continued in this direction till the very end of the course unit. We have named this tendency 'consistency of direction'.

**Linguistics** In linguistic theory consistency of direction is never mentioned as one of the conventions in linearization. However, many examples of sequences are discussed that are connective in nature and also consistent of direction. For instance, when giving route directions, speakers consistently follow a 'source to goal spatial connectivity' (Levelt, 1989, p.139). When describing unfamiliar countries as depicted on a geographical map, speakers quite frequently describe the countries in a west-to-east order. If, however, for instance, their native country lies in the eastern part, speakers generally start east and discuss the countries more and more remote from their native country. Here, they consistently follow an east-to-west order. Two sequences in reverse directions, both are, however, consistent of direction.

**Cognitive science** Connectivity was seen as "a general ordering principle in perception and memory" (Levelt, 1989, p. 142). Frequently, consistency will be a direct result of the desire to preserve connectivity. When, for instance, describing a linear (non branched) structure of related topics, full connectivity inevitably leads to consistency (see e.g., section 5.4.1.1).

### 4.10.3 'Natural' direction

**Analysis of written material** Besides the observed consistency of direction, for a limited number of rationales an evident direction preference was observed. For example, all generalization-specification structures in the study were found to be traversed in a top-down direction. All historical and procedural structures were described in a chronological order. Apparently, some classes of structure could be observed to have an inherent associated 'natural' direction.

**Linguistics** In the theory on linearization this finding is labeled as the convention of 'natural order' (Levelt, 1989). 'Natural order' refers to an order assumption connected to a structure type. Generally, this assumption is shared by speaker and addressee. For instance, the description of the following two events, *they left the restaurant, the dinner was served* will generally be interpreted chronologically, thus the dinner being served after they left the restaurant. This interpretation will predominate, even though the scheme is somewhat unfamiliar and nothing was said about the order of events. The interpretation is based on the tacit agreement that a historical structure will be discussed in chronological order if not explicitly said otherwise. The advantages of such a tacit agreement are obvious, again information about the relation between events can be left out.

No general definition of natural order exists, what counts as natural ordering is different for different types of domains. But, many so called 'natural' orders can be traced back to process-related determinants. The source-to-goal order when giving route directions and the bottom-to-top 'climbing' order when describing one's apartment building are examples of process determined descriptions of, in this case, spatial structures.

**Cognitive science** The cognitive basis of 'natural order' is addressed by Levelt (1989). Levelt poses the question 'why is natural order so natural' and remarks that the tacit agreement on natural order may be due to universal principles of memory organization, or to more culture-specific 'scripts' (p. 139). Referring to memory organization, if people indeed organize and remember related events as temporally ordered structures, it should be relatively easy or natural for a speaker to retrieve the information in that order. Similarly, for an addressee to decode it in that order. A study by Thorndyke (1977) provides some evidence for the storage of information as scripts, temporally organized structures. Thorndyke, for instance, showed that an entire story was remembered much better than a list of all its sentences in random order. The question is why? Kintsch, Mandle and Kozminsky (1977) revealed that stories generally have a 'natural' order; the events (or episodes) in the story form a temporal, sometimes causal structure. In a story, the episodes are generally presented in a chronological way. It is not unlikely that the reason that such temporal structures are remembered better, is that the manner of presentation is in accordance with the way information is stored.

### 4.10.4 Structure-relatedness as norm

In the previous sections we have discussed the findings of the analysis of written instructional material in the light of related disciplines. This discussion yielded some arguments to support that connectivity, consistency of direction, and 'natural' order characterizes 'optimal' sequencing.

Arguments from linguistics have to do with economy in interaction. It was argued that the conventions of connectivity and 'natural direction' streamline discourse. This does not necessarily imply that the use of these conventions is optimal for the organization of educational material. However, it is argued that negligence of generally accepted conventions may lead to confusion. Norman (1988), for instance, argues and illustrates that a design may be ineffective due to negligence of conventions. Once a convention on, for instance, the function of mouse buttons is accepted by the user community, a switch of convention produces great confusion and error. Similarly, if a speaker discusses two completely unrelated topics after one another without making explicit that the topics are unrelated, thus violating the convention of connectivity, many listeners will wrongly conclude that the topics are related. Violation of conventions will readily lead to error (cf., Winn, 1983).

Finally, and probably most important, among others Neerincx (1995) has argued that adherence to conventions allows functioning at the so called 'skill' level (Rasmussen, 1983), where highly automated procedures are called upon. Violation of commonly accepted conventions would then require far more mental effort to accomplish a task, since no automated procedures can be used.

The bottom line is that one should only deviate from conventions in exceptional circumstances. As for now, we see no such reasons why conventions concerning discourse should not apply to the organization of material for information space exploration.

Finally, arguments from cognitive science have to do with assumptions on inherent limitations of the cognitive system. Anticipation on such limitations should ease learning at a level that requires minimal mental effort. However, the arguments presented in the previous section alone provide no convincing evidence for the actual existence of these inherent limitations. Still, if we add the findings from the study of written material, arguments from linguistics and the weak argument from cognitive science, we believe to have a basis for prescriptions for support.

# SEQTool: the design of non-directive support for exploration

# 5

## 5.1 Introduction

In the previous chapter a pattern of so called 'structure-related' sequencing was outlined. The term 'structure-related' sequence was entered as an umbrella notion for a pattern that could be characterized by connectivity, consistency of direction, and natural direction. This pattern was put forward as norm behavior for information space exploration. The present chapter describes the design of a tool that aims at supporting students in a non-directive manner to explore in a structure-related way. The design of this tool is inspired by the wish to tackle the problem of disorientation in unstructured learning environments such as hypermedia. Students seem to have trouble to cope with the freedom offered by these relatively new media (chapter 1). Their behavior is frequently less methodic than desired and, as we postulated in the previous chapters, this affects the acquisition of knowledge of structure.

Together with the necessity of a methodic approach, a strong demand for flexibility was expressed, two seemingly conflicting desires. Meeting both requirements could only be accomplished by providing an unobtrusive, and thus non-directive form of support. In this chapter the design of a graphical overview is sketched that is supposed to realize such a form of support. In the design of this graphical overview, the deliberate use of conventions plays a central role. Conventions with regard to the perception of graphics are used to design an environment that makes students voluntarily choose a structure-related trajectory. The use of such conventions enables support to be unobtrusive, the environment preserves full flexibility of exploration. Hence, it is thought to be a true example of a cognitive tool.

## 5.2 Design for support

The problem of disorientation, getting lost in hyperspace, is one of the main concerns in the hypertext field. Various types of solutions have been proposed to help students to overcome the complexity of exploration. A majority of the current applications provides 'concept maps' or graphical overviews as support for orientation and planning (see for a discussion of applications, potentials and problems (Conklin, 1987; de Young, 1990)). One of the major problems with these overviews is that the user is confronted with the full complexity of today's usually large systems. Attempts are made to reduce this complexity by reducing the amount of information that is accessible at a certain moment in time. An example of such information space reduction is found in the 'fish eye' metaphor (Furnas, 1986). Furnas describes a graphical overview that is deformed, it has a sharp focus area that present foreground material and a vague surrounding area that presents background material. Even more restrictive are the 'guided tours' as implemented by Allison and Hammond (1989), (see also Arents & Bogearts, 1993). In addition, several authors propose means to keep track of the history of exploration, to leave 'footprints' (Foss, 1987; McAleese, 1989) sometimes combined with means to mark important sections (Rouet, 1990) and to annotate the material studied (Monk, 1990).

Graphical overviews combined with information reduction, histories, and markers seem essential to overcome disorientation. Unfortunately, little study has been done to assess the merits of these forms of support. What we know from evaluations of support tools for exploratory learning in simulation environments is that one has to be extremely careful with adding support tools. In some cases support was even found to be detrimental to learning (de Jong *et al.*, 1993a). Explanations for this effect were sought in additional demands on cognitive capacity and it was speculated that the support tools might even have distracted the students from the learning tasks.

A first criterion for the design is thus that one should be extremely careful with imposing extra cognitive load on students (cf., Neerincx, 1995). Besides, support should not distract from the main task. Some of the early graphical overviews lacked a directly accessible link between hypertext fragments and the representation of those fragments in the graphical overview. Consulting the overview then readily leads to distraction. We will seek to avoid distraction by making support an integral part of the learning environment.

Chapter 2 listed several requirements for fruitful information space exploration. One of these requirements, that of non-directive support, stated that 'support should allow for flexibility and it should be unobtrusive'. A danger of the guided tours and fish eye views is that these force students into patterns that may not suit their needs. Structure-related exploration should certainly be preferable over the ad hoc unmethodical exploration of those 'lost in hyperspace'. Nevertheless, those students that are not lost may be deprived by being forced into a structure-related pattern of exploration. In section 2.3.2 it was argued that system imposed sequence might readily interfere with the knowledge acquisition process of the individual learner. For example, studies by Mager (1964) and Lodewijks (1983) have shown that students working with a self-imposed sequence in a relatively manageable environment did substantially better than students working with an imposed 'structure-related' sequence.

Unguided exploration may, with insufficient prior knowledge, lead to an unmethodic form of exploration, whereas a too directive form of support may 'alienate' the student from the material. Hence, in the design we should strive to find the delicate balance between guidance and student autonomy.

## 5.3 Underlying principles

Balance between guidance and student autonomy was pursued by developing a so called 'meaningful' graphical overview of the hypertext structure. In this type of overview the layout of the representation is manipulated in a way that is likely to lead to a structure-related form of exploration while still allowing students to deviate if this better suits their needs. Besides, such an advanced overview might have a function in supporting connection to prior knowledge. With the 'meaningful overview' we hope to realize the type of *non-directive* support that was advocated by amongst others (Njoo, 1994). The following paragraphs describe principles underlying the design of meaningful overviews.

In the hypertext field several measures for support have been proposed. At this moment the graphical overviews have taken lead in helping users to gain a sense of the structure of the domain. It is assumed that visualization can be a highly valuable means for overcoming disorientation and by that, non-systematic exploration. Visualization, or better *visibility* is a key concept in the work of Norman (1988). Norman argues that the internal functional structure of a system must be visible externally to allow the user to make deliberate decisions on how to handle the system. Visibility makes a difference. This is very evident when comparing the user friendliness (at least for novices) of a menu based interface to that of a command driven system. In line with Norman we argue that the need for visibility also holds for an internal domain structure that is to be explored. Here too the student has to be able to oversee the structure and to be able to decide on the trajectory of exploration. A hypertext system that consists only of 'electronic' cards with a description of isolated topics fails to make the overall content structure visible to the user.

Visibility of the internal domain structure of a hypertext might well enhance exploratory behavior. Indeed, benefits of visualization of the links in a hypertext structure have been shown in a study by Zhao et al. (1993). Besides, Conklin (1987) argues (p. 39) that graphical browsers "rely on the extremely high developed visual-spatial processing of the human visual system". "Users orient themselves by visual cues, just as when walking or driving through a familiar city."

Generating a visualization of the structure of an extensive domain is not trivial. Those who discuss the generation of graphical overviews address the technical and conceptual problems involved in the display of large structures (see e.g., Pintado & Tsichritzis, 1990; Christensen *et al.*, 1993). With extensive domains, a display of nodes and links without underlying structure too easily gets opaque itself. The display of large numbers of links easily results in highly cluttered graphics. Thus, a layout mechanism is needed that clearly reflects the structure of the content. However, as Conklin indicates (p. 39), "there is no natural topology for an information space." In other words, the field lacks principles for 'meaningful' layout.

In the following paragraphs we shall come up with some principles that may be used to generate a 'meaningful layout', a layout that gives insight in the internal structure of the domain and simultaneously promotes structure-related exploration.

Visualizations have two aspects that determine their merits with regard to learning: 1) a visualization may convey meaning in its own right, and 2) a visualization will affect the exploratory trajectory. Figure 5.1 outlines these aspects and the way they are supposed to affect learning, or more specifically, the acquisition of knowledge of structure.

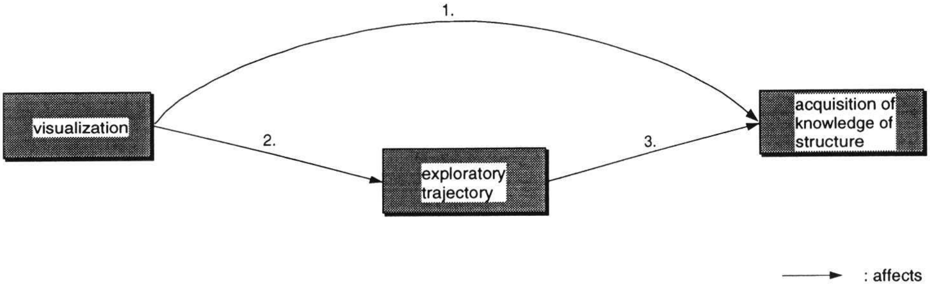



Figure 5.1: Direct and indirect influences of a visualization on acquisition of knowledge of structure

This scheme outlines the assumptions that are central to the design of a 'meaningful layout'. These assumptions will be subject to study in the experiment described in chapter 6.

In the following sections, firstly the direct link between visualization and learning (*Relation 1*) is discussed (section 5.3.1). Secondly, the link between visualization and exploratory trajectory

(*Relation* 2) is discussed in section 5.3.2. Thirdly, the link between structure-related exploration and learning (*Relation 3*) is discussed in section 5.3.3.

### 5.3.1 Relation 1: Visualization affects acquisition of knowledge

Visualizations may be powerful means in their own right to convey meaning. Diagrams 'exploit the human visual skill', as Nardi and Craig (1993) remark (p. 22), visualizations or "Visual formalisms take advantage of our ability to perceive spatial relationships and to infer structure and meaning from those relationships". In studies that compared textual with diagramatical representations, several advantages of diagramatical representations are mentioned. Advantages were assumed to lie in *processing* and *preservation* of information. Both aspects will be discussed below.

**Processing advantages** Norman (1993) contended that graphics are cognitive artifacts that can enhance performance by reducing cognitive overhead. For graphics, reduction in cognitive overhead occurs when perceptual inferences replace complex cognitive tasks (Lohse, 1993, p. 385). In this line, Larkin and Simon (1987) have pointed out that different kinds of representations, though being informationally equivalent, may be 'computationally' different. That is, between representations, differences in the speed of drawing inferences may occur. The statement on differences in speed of inferencing is supported by a study by Winn (1993) who compared inferences made on the basis of a textual and a diagramatical representation of a family tree. The economy of the diagramatical representation became evident by the finding that students that used this representation answered questions on kinship significantly faster than those who worked with the textual representation. The differences in speed were ascribed to the laborious search for information in text as well as to the fact that only the users of textual information had to keep information in working memory to correctly answer the kinship questions. Whereas inferring kinship from a diagram is seen as a straightforward perception process, inferring kinship from text demands more complex cognitive activities. Indeed, Larkin and Simon make clear that for diagrams and text, while being informationally equivalent, the more dimensional diagram may be far more economical in its support for search for information. "The advantages of diagrams, in our view are computational" (Larkin & Simon, 1987, p. 99).

**Information preservation advantages** Although text and diagrams may in the end contain the same information, some information is better preserved by a diagram than by text. Larkin and Simon (1987), for instance, put forward that diagrams are superior in preserving information on geometric and topological relations. Textual representations are fine for preserving information on one dimensional relationships such as temporal relations, whereas diagrams are much better in preserving two and three dimensional relationships. As hypertext structures are more likely to be multidimensional and ill-structured than clear cut one dimensional, it is assumed that diagrams may add to preserve information on those multidimensional structures in hypertext.

A well designed visualization may directly benefit learning, but also indirectly, by facilitating methodical exploration (see the following section). In the experiment in chapter 6 we assess whether a well designed visualization positively affects learning, irrespective of indirect effects resulting from improvement of the exploratory behavior.

### 5.3.2 Relation 2: Visualization affects exploratory trajectory

We have stressed the need of a non-directive form of support to provide users with all the flexibility they might need. Norman (1988) suggested the deliberate use of constraints and conventions to guide the behavior of people in a non-directive way. For example, the designers of the floppy disk deliberately used physical constraints, for instance, by adding notches to make sure that a floppy disk could only be put in a drive in the correct way. With using constraints in this way, no directions on putting the floppy in the machine were needed. The constraints made the correct way of handling evident. In a similar way, cultural conventions can be used to guide behavior.

A convention we refer to is that of *reading direction*; people from western cultures will generally read from left to right and top-down (see e.g., Levelt, 1982). This learned behavior has effects that go beyond the reading of text. A predominant left-to-right direction is also found in search in graphical overviews (Winn, 1993). Evidence for transfer of reading direction to diagram perception comes from studies that investigated diagram perception among people whose languages read from right to left. With Arabic native speakers, graphics are processed right to left (Tversky *et al.*, 1991). The same authors remark that studies in development of writing and drawing show that the reading direction preference is established as children acquire literacy, from which we can conclude that the convention of reading direction is indeed learned.

An awareness of the 'reading direction' convention is extremely useful for design and we will show in section 5.4.1.1 how the reading convention can be used to get users to explore in a structure-related way. Frequently, learners are well able to regulate their own learning (chapter 2), the question is whether they need support to let their exploration be methodical, more specific, be structure-related. In the experiment in chapter 6 is investigated whether a meaningful layout actually enhances structure-relatedness of exploration.

### 5.3.3 Relation 3: Structure-related exploration affects acquisition of structural knowledge

The relation between structure-related exploration and acquisition of knowledge was addressed in section 2.2.1. It was postulated in this section that the acquisition of knowledge of structure is enhanced by having sequence 'closely relate' to that structure. 'Closely related' to a structure was operationalized in terms of connectivity, consistency of direction, and the pursuing of a 'natural' direction (chapter 4). This structure-related exploratory behavior was expected to affect acquisition of structural knowledge only. Hence, the expected effect on learning is specific.

In the experiment in chapter 6 we will test 1) whether an effect of structure-related exploration occurs and 2) whether this effect is indeed as specific as assumed.

## 5.4 Design

In the previous sections a model was described that contained aspects that were intended to directly and indirectly affect the acquisition of knowledge. A well designed visualization could positively affect acquisition, by enhancing information preservation and processing. Concurrently, such a visualization might affect structure-relatedness of behavior. Finally, structure-relatedness of behavior might affect acquisition of knowledge of structure.

The following sections describe the way in which we arrived at prescriptions for the design of visualizations. Briefly, design of visualization is guided by the intention to optimize the influence of the visualization, both on the acquisition of knowledge and on the structure-relatedness of exploratory behavior.

## 5.4.1 Techniques

### 5.4.1.1 Visualization for structure-related exploration

In section 5.3.2 the deliberate use of conventions was suggested for guiding exploratory behavior in an unobtrusive way. In this section we will show how a reading convention may be used to make learners voluntarily explore in a structure-related way. Prescriptions for visualization for structure-relatedness were derived from a pilot study on traversal of different representations. Below we will briefly sketch the results of this study, followed by the resulting prescriptions.

The study on traversal provided subjects with different visualizations of two so-called 'primitive structures'. The notion of **primitive structures** is a crucial idea in this study. The idea was that domains could be described in terms of a limited set of basic structure types. In this work two primitive structure forms have been defined, namely a **branched** and a **non-branched** structure. The distinction between branched and non-branched structures was made since it was observed that it does make a difference in traversing a structure whether one deals with linear or branched structure forms (see Levelt, 1982).

The subjects in this study, 5 psychology freshmen and 4 colleagues, were presented with several visualizations of the two primitive structures. The aim was to get an impression of trends in the order in which the subjects would perceive the entities in the structures. They were asked to describe the representations so that these could easily be reproduced by someone listening to the description from tape. It was shown by Tversky and Kugelmass (1991) that such a description of elements corresponds to the subject's 'perceptual exploration', that is, the manner in which the subjects would explore the graphics themselves.

**Visualization and connectivity** The way in which a structure is visualized influences connectivity of exploration. Figure 5.2 shows material and some results of the aforementioned study. Here two different representations of a non-branched structure consisting of five related entities are given. The outcomes of this experiment are summarized in Figure 5.2. Below the representations of both structures an indication is given of the way the subjects in this study traversed the representations (arrows indicate the direction of traverses, and the numbers below the arrow patterns refer to the incidence of that particular pattern).

As shown in Figure 5.2, eight subjects from the group of nine read the elements of Representation 1 from left to right, and thus fully connective. The remaining subject also read fully connective, but from right to left. Representation 2 of an identical structure appeared to 'break' the connective pattern. Four subjects out of 9 started at the 'central' node, the node in the upper left corner, went from there in a connective way to the right hand end, 'jumped' back to the central node and proceeded downward. Another 2 subjects started at the central node, went down, got back up again and then proceeded to the right. Only 3 out of 9 thus followed a fully connective path.[1]

If we analyze the differences in outcomes using the measure for connectivity as described in section 4.6.2.2, Representation 1 yields a mean connectivity of 1 ($SD = 0$) and representation 2

[1] Indeed, if we use the unbiased measure for connectivity as presented in section 4.6.2.2 all trajectories are fully connective. However, this nuance was added to cope with branched structures. For non-branched structures direct connectivity is to be preferred.

of .89 ($SD$ = .09). This difference is significant ($t$ = 4.00, *df* = 16, $p < .00$).

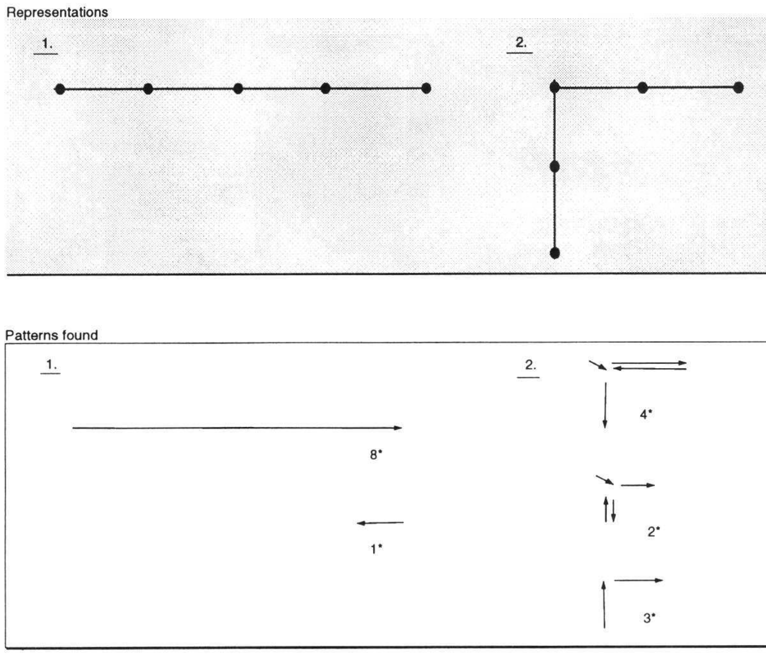



Figure 5.2: An example of traverses along two different representations of an identical structure

This pilot study used two different representations of an identical structure, one representation lead to connectivity, the other certainly not in all cases. Moreover, the behavior in Representation 1 is to a certain extent predictable, while that of Representation 2 is not. For the design of non-directive support, predictability of behavior is crucial.

**Visualization and consistency of direction** Visualization is also observed to affect the direction of traversal. In describing the results we will make a distinction between branched and non-branched structures.

**Non-branched structures** Referring again to Figure 5.2, it is also evident that Representation 1 lead to 'consistency of direction', whereas Representation 2 did not. Again, if we use the measure for consistency as described in section 4.6.2.1, with as norm for consistency that all four possible traverses had to be in the same direction, a mean consistency of 1.00 ($SD$ = .00) is obtained for Representation 1, versus .33 ($SD$ = .50) for Representation 2. This underlines that consistency within Representation 1 was higher ($t$ = 4.00, *df* = 16, $p < .00$).

Moreover, rotation of Representation 1 could not deteriorate consistency of direction. Whether the orientation was horizontal, diagonal or vertical (as in Figure 5.4), without exception, the direction once chosen remained.

**Branched structures** With respect to branched structures, it was found that tree- representation (as shown in Figure 5.3) generally resulted in consistency of a root-leaf direction.

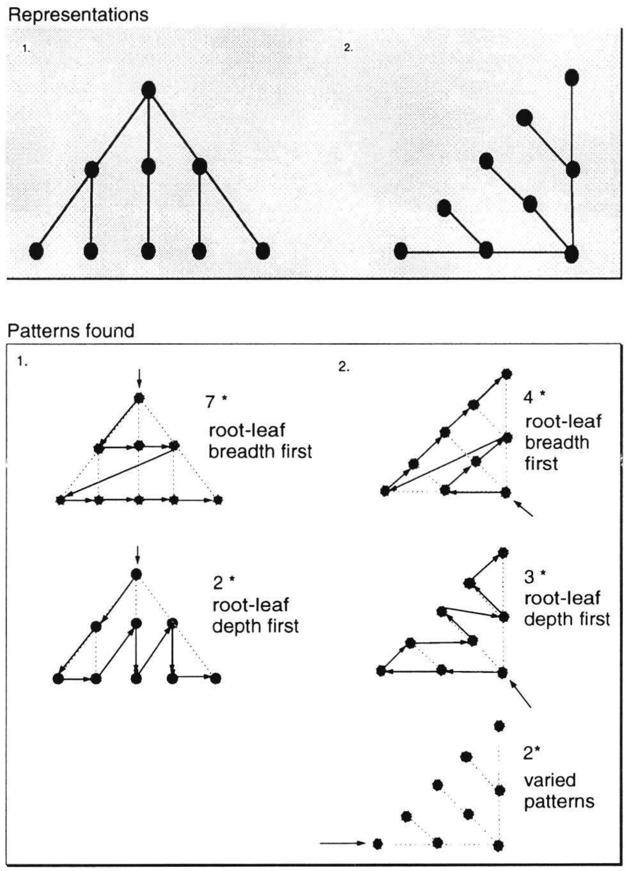



Figure 5.3: Two representations of a hierarchical structure with different orientations

While describing the various tree structures, the subjects showed a strong tendency to start at those nodes that were sources of branches. It was observed that the root of a tree structure was a prevalent starting point when describing that structure. This finding was general, irrespective of the orientation of that tree. Orientation was manipulated to find out whether reading direction preference would overrule the obvious root-leaf direction preference for branched structures. To explore such dominance, the experimental set included a tree with its root in the lower right hand corner as depicted in Figure 5.3. This latter orientation was chosen so that left-to-right reading would promote a leaf-root direction. Nevertheless, the preference for a root-leaf was near unanimous (7 out of 9). Hence, the presence of branches must have overruled a reading direction in favor of a root-leaf direction.

Analysis of consistency of direction (with a norm $B \geq 6$) results in maximal scores (mean $= 1$,

$SD = 0$) for both representations. Thus, on this basis we may conclude that orientation of branched structures does not affect direction.

**Visualization and natural order** The trajectories presented in Figure 5.2 have illustrated that the layout of the visualization of a structure may affect connectivity and consistency of direction. The following example will show that the orientation of visualizations of linear structures can be used to guide people to traverse in a certain direction. The reading metaphor can be used to get students to pursue a natural direction. The examples in Figure 5.4 of traverses within differently oriented linear visualizations of a non-branched structure show that the orientation of a representation affects the way the representation is explored.

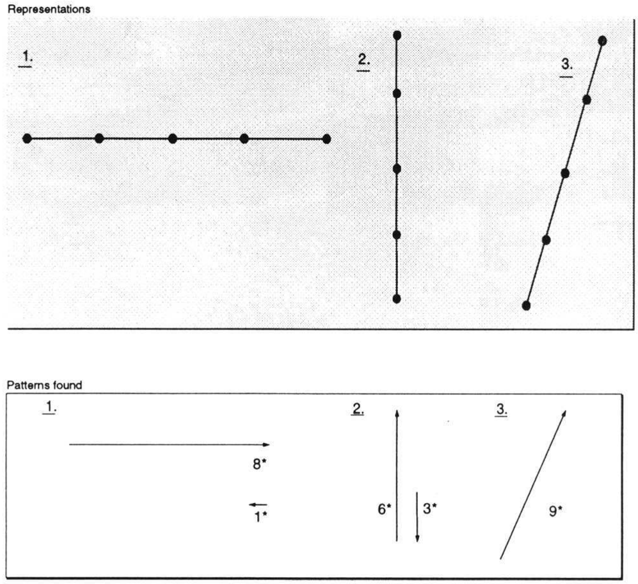



Figure 5.4: Similar representations, different orientations

In a horizontally oriented linear Representation 1, as said before, an 8 out of 9 left-to-right preference was found. Surprisingly, in contrast to the results reported by Winn (1993), in the vertically oriented linear Representation 2 no such evident direction preference was found. The prediction was that, due to the use of a reading metaphor, an evident top-down direction preference should be found. Nevertheless, only 3 out 9 subjects actually choose a top-down direction, the other 6 chose a bottom-to-top direction. A diagonally placed representation (3) resulted in a fully consistent (9 out of 9) direction preference for a bottom-left to top-right direction.

Analysis of direction preference, using the measure as defined in section 4.6.2.1 results in the following indications: Representation 1 (mean $= .77$, $SD = .67$), Representation 2 (mean $= -.33$, $SD = 1.0$), and Representation 3 (mean $= 1$, $SD = .00$). Analysis of variance reveals an effect of orientation ($F(2, 24) = 9.54$, $p < .00$). Posthoc analysis (Scheffé) indicates that the differences can be found between Representations 1 and 2, and between 2 and 3. We may thus conclude that the orientation of a further similar representation affects the way students traverse these structures.

Due to the fact that horizontal and diagonal orientations of linear representations have evident associated direction preferences, manipulation of the orientation of a representation can be used as a means of guiding students to traverse a structure in a certain direction. For example, if students could best explore the events of a temporal structure in a chronological order, one might display those events so that the event most remote in time is displayed left and successive events be displayed to the right hand side of their predecessors. The student will then generally read the events from screen in a chronological, and thus natural order.

**Conclusions** We have illustrated how both *layout* and *orientation* of a visualization of a structure may affect the way learners explore that structure.

The study described above has lead to a small set of rules for layout that aim at optimizing the structure-relatedness of information space exploration. The rules define which type of layout and orientation lead to predictable behavior and subsequently state which kind of behavior can be expected.

- **Non branched structure** *If a structure is non-branched, for behavior to be predictable the layout should be linear and the orientation may be horizontal or diagonal. Any linear horizontally or diagonally oriented structure guarantees connectivity and consistency of direction. For a natural direction to be pursued, the representation should be so that the element to be visited first is at the left hand side.*

- **Branched structure** *If a structure is branched, the exploratory behavior is not so much affected by orientation. Generally, one may expect a root-leaf direction preference (see also Levelt, 1989). Behavior will be more predictable, however, if a branched structure is oriented so that its root is in an upper or left hand side region.*

#### 5.4.1.2 Visualization for information preservation

In the previous sections we described principles for the design of visualizations that resulted from the requirement to guide exploration to be structure-related. Complementary principles result from the demand (section 5.3.1) to design visualizations so that information preservation and processing is optimized.

In section 5.3.1 it was argued that pictures can be a highly economic means of conveying information, they may be 'worth ten thousand words' (cf., Larkin & Simon, 1987). Moreover, the combination of text and pictures might be even more beneficial. A final point that arises from the research on perception is that the form of a visualization is critical to its benefits. Although many studies reveal that the effectiveness of a particular diagram is contingent upon the user's goals (Lohse, 1993; Winn, 1993), other work shows that some general statements can be made on the effects of format of a diagram on the interpretation. We will discuss these statements to come up with principles for the design of the format of visualization that best facilitates appropriate interpretation.

A highly relevant study in this regard is the work by Winn (1993; 1983) on diagram conventions. This work shows that the interpretation of diagrams is strongly guided by convention. That is, the layout of the elements in a diagram highly influences the interpretation of that diagram. Winn presented students with the task of forced-choice interpretations of two symbol diagrams. Figure 5.5 shows two of the diagrams (as reconstructed from the description) from the sets of material presented. Students were forced to choose amongst three possible interpretations; 1) $A$ causes $B$, 2) $A$ is a superclass of $B$ ($A$ is a $B$), or 3) $A$ has a $B$.

Figure 5.5 shows two of the diagrams (as reconstructed from the description). Students were forced to choose amongst three possible interpretations; 1) $A$ causes $B$, 2) $A$ is a superclass of $B$ ($A$ is a $B$), or 3) $A$ has a $B$.

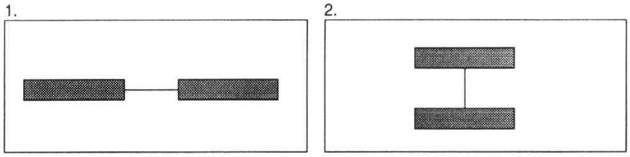



Figure 5.5: A reconstruction of two of the representations used by Winn

The results revealed a strong bias towards certain layout-interpretation combinations. Representation 1 was generally interpreted as a causal structure, where the left hand side symbol represented a cause and the right hand side symbol an effect. Representation 2 was mainly interpreted as class-subclass structure where the class would be represented by the top symbol and the subclass by the bottom symbol.

We may conclude from Winn's study that the layout of a visualization does make a difference in interpretation. Winn claims that interpretation is strongly guided by convention. Winn has shown that at least for causal and class-subclass relations such conventions exist. Here, and repeatedly later on, we will make a point for adherence to conventions, as violation of conventions might readily lead to confusion and error (see 4.10.4). Hence, in the construction of visualizations, *diagram conventions* may not be neglected.

More general, but also weaker, indications for diagram constructions result from the work by Norman (1988; 1993). With respect to diagram construction, Winn (1993) already mentioned the need for 'notational' formats, formats that establish an unambiguous relation between an internal structure and its external representation. With a similar intention, Norman mentions the need for *natural mapping*, stating that a representation should have a direct relation to the structure represented. "Experiential cognition is aided when the properties of the representation match the properties of the thing being represented." (Norman, 1993, p. 72). The representation should visualize nothing more and nothing less than all relevant details of the underlying structure. Certainly, the representation may not wrongly suggest non existent features.

The main aim of this section is to come up with *visualization templates* that can be used to create visual overviews for hypertext structures. Principles of adherence to *diagram conventions* and *natural mapping* will play a major role in the design of the form of those templates. In addition, several additional principles were derived from the requirement for the visualization to support structure-related exploratory behavior.

### 5.4.2 Visualization templates

**Non-branched structures** With the requirement of natural mapping in mind, we will discuss several possible representations for non-branched structures. In Figure 5.2 we presented two possible representations and studied exploratory behavior that was provoked by the different representations. There, we already concluded that a linear representation was to be prefered over a so called 'hooked' one since it promoted more predictable behavior and more consistently lead to a 'structure-related' exploratory trajectory. Predictability of behavior is crucial as our aim is to guide students in a non-directive manner.

In this section we will again discuss several possible representation formats for non-branched structures, now with the criterion of natural mapping in mind. The criterion of 'natural mapping' as well as that of 'predictability of behavior' guides the selection of a single representation to be used as the template for non-branched structures.

Figure 5.6 presents three types of representations of a non-branched structure. Representation 1 is a linear representation, 2 a so called 'hooked' one and 3 is a representation with randomly positioned entities. It is argued here that Representation 1 yields the most natural mapping to the internal structure. Representation 2 wrongly suggests that the central node is not similar to the other nodes, the node seems the source of a branch. A representation that promotes an incorrect interpretation of the underlying structure, violates the principle of natural mapping.

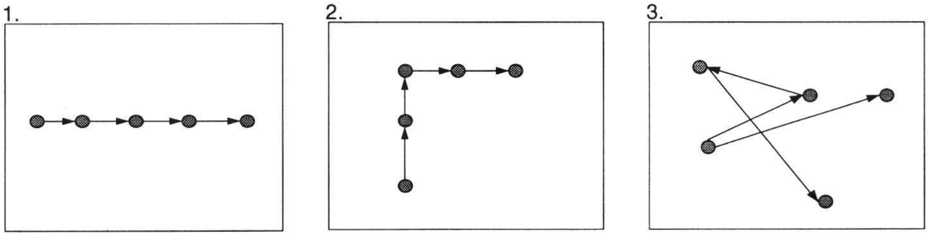



Figure 5.6: Three representations of an identical non -branched structure

Representation 3 may wrongly suggest differences in semantic distance amongst relations or may be too chaotic to suggest anything at all, being right or wrong. In addition, it is less preferable for reasons of efficiency of information processing (see section 5.3.1). Larkin and Simon (1987) claimed that the speed of problem solving inferences could, amongst other things, be enhanced by the grouping of information that is used together, thus avoiding large amounts of search for the elements needed to make a problem solving inference. From this, we have derived the above mentioned principle of adjacency: related topics should be grouped. Representation 3 violates the 'adjacency' principle. In Representation 1 related entities are closer, more adjacent than non related entities and therefore Representation 1 is preferred over Representation 3. All in all, Representation 1 is seen as the best natural mapping onto the non-branched primitive structure.

- *Hence, if a structure is non-branched and if no further information is available than that it is composed of entities and relations of similar type, a linear representation as in Representation 1 is chosen to act as visualization template.*

**Branched structures** Branched structures can also be depicted in various ways, where some ways will provide a more natural mapping than others. To illustrate this, two tree representations are given in Figure 5.7. The represented branched structure is a hierarchical one and no differences exist with respect to semantic difference between related pairs of entities. It is argued here that Representation 1 is a more 'natural' representation of the hierarchy than 2. In Representation 1 the vertical dimension reflects the level of the entities in the hierarchy, whereas in Representation 2 the location of the entities has no relation to the level of those entities in the hierarchy. Besides, the differences in line length in this representation wrongly suggest differences in semantic distance.

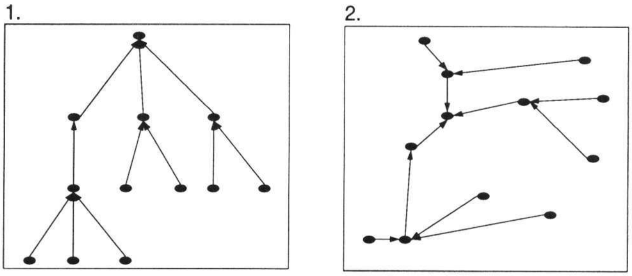



Figure 5.7: Two representations of an identical branched structure

- *Hence, the template for branched structures should depict related entities at similar spatial distance, or at the same level as in Representation 1. Only if the space on a screen does not allow to depict the names of nodes alongside, the names will be depicted stair-wise.*

### 5.4.3 Orientation of the templates

Having defined two types of templates, finally some words should be addressed to the *orientation* of these templates. Orientation refers to the placement of the template on the screen. For instance, linear representations can be placed horizontally, vertically, and diagonally. We argued that orientation affects exploratory behavior (see section 5.3.2), in addition we will show that orientation also affects interpretation.

Referring back to the notion of diagram conventions (Winn, 1993, see section 5.4.1.2), we may state that it is unconventional to orient a tree representation for a generalization-specification structure horizontally, where the root is placed left or right of the leaves. Previously, we have argued for adherence to conventions, as violating conventions might easily lead to confusion and error. Hence, orientation should try to conform to conventions on diagram interpretation as much as possible. Unfortunately, the study by Winn only provides conventions for causal and generalization-specification structures. Further study should reveal conventions for the interpretation of other structure types. We can thus only provide rules for the orientation of generalization-specification and causal structures and end with the statement that other structure types are likely to be accompanied by similar conventions.

In consequence, the following rules for orientation can be given:

- *If the structure is non-branched the linear template may be oriented horizontally or diagonally, where the entities to be visited first should be located at the left hand side.*

- *If the structure is non-branched and causal in nature, the linear template should be oriented horizontally, where the entities representing 'cause' are to be located left of the entities representing 'effect'.*

- *If the structure is branched, the tree template is generally oriented so that the root is located at the top or in the upper left hand corner.*

- *If the structure is branched and is a generalization-specification structure, the tree template should be oriented so that the root is at the top.*

With visualization templates and some rules for orientation, a next problem is to mould complex structures into the templates. The application of visualization was providing graphical overviews for hypertext structures. A vast majority of hypertext structures will be ill-structured (cf., Spiro *et al.*, 1991) and thus a major problem to be solved is a reconstruction of a hypertext domain in terms of the primitive structures defined in this work. As this problem was outside the scope of this work, we will only come up with a partial solution, a solution that works for simple structures but certainly not for highly complex structures. In the next section we shall describe the layout algorithm that reconstructs the structure and subsequently visualizes it, while using the templates and orientation rules. The current chapter ends with an example of an application of the algorithm.

### 5.4.4 The layout algorithm

In this section we shall briefly describe the resulting layout algorithm that was implemented in an authoring system named 'SEQTool'.[2]

In overview, the algorithm in SEQTool essentially analyzes a domain for the presence of so called 'primitive' structures. If a nested set of primitive structures is detected, SEQTool moulds these structures into the standard visualization templates. Finally, it manipulates the orientation of these templates so that the student's exploration is likely to follow a natural direction. Each of these steps is discussed in turn.

**Detection of primitive structures** A first step is the detection of primitive structures. As primitive structures, by definition, consist of entities linked by relations of the same type, SEQTool creates an inventory of all relation types present in the hypertext structure. This results in a number of so called clusters, where each entity may occur in more than one cluster. SEQTool then analyzes per cluster whether one or more primitive structures are present. If all entities can be reached from one another then just one primitive structure is found, otherwise the cluster has to be broken down. This is done by randomly selecting an entity from the cluster and finding all directly and indirectly related entities. This procedure is repeated until no entities are left.

A next step is to detect whether structures are branched or not. If one entity in a structure has more than one incoming or more than one outgoing link, the structure is judged to be branched.[3]

**Nesting and orientation** Once all separate primitive structures have been detected, the nesting problem comes in. Indeed, all isolated primitive structures can be represented separately, however, if the connection between structures is essential a nested visualization should be created. We discuss only the nested variant since the depiction of isolated templates is straightforward. For nesting, the system first finds the predominant primitive structure on the basis of a calculation of centrality of each entity according to in-degree (see Sprenger & Stokman, 1989). This calculation takes all relations present into account, irrespective of their type. The entity with the largest centrality is seen as the central entity of the predominant structure.

Substructures are found in a similar way by disregarding the relations of the previously found predominant structure. It must be noted that the current decomposition mechanism is limited in

[2]SEQTool was implemented in SWI-Prolog (Wielemaker, 1991) and the Graphical UI language XPCE (Wielemaker, 1995)

[3]For the moment, some special structures, such as spiral or circular structures, are to be regarded as special cases of the primitive ones. However, the system could certainly be improved by providing visualization templates for these special structures.

scope. It, for instance, fails to handle multiple inheritance structures.

A final step in the algorithm is the nesting and orientation of the representations of primitive structures. The current version of the SEQTool handles only the nesting and orientation of the first two nested structures, the remaining substructures need to be laid out with the support of an author. For nesting, the visualization template of the prevailing structure will act as a basic visualization. Substructures are made to fit into this basic visualization, taking into account considerations on orientation.

To illustrate this, in the example in Figure 5.8, for instance, a tree template was used as a basis, and a linear template at the first layer was made to fit in the tree. The linear template was placed horizontally. This may seem trivial as no other options are available. However, the tree template could have been oriented with its root located at the left hand side. With this, the linear template located in the first layer of the tree should have been oriented vertically. This would, however, have diminished the predictability of behavior in this structure.

As was remarked before, manipulation of orientation will mainly affect the direction of exploration in linear structures. Therefore, if the predominant structure were linear, the system would, using its rule set on natural order, place the visualization template so that the elements first to be explored by the user would be located at the left hand side. In compound structures, for instance, a tree structure that incorporates a linear structure in one of its layers, the preferred orientation of that linear structure is used to determine the left-to-right positioning of branches.

**Example** In this section we will describe the construction of a 'meaningful layout' of an example domain. For this illustration we have used the domain of operation of fuel supply systems. This domain was used in the experiment that will be described in chapter 6.

Without going into the details we shall outline the structure of the domain. The predominant structure is a generalization-specification structure with at the top a 'place holder' and at the next layer a non-branched structure describing processes in measure and control systems in general. A next lower level yields an elaboration of the former by describing measure and control processes specific for fuel supply system. Finally, three causal branched structures at the bottom indicate correct and faulty processes as may occur in the fuel supply system.

Because the generalization-specification structure was found to be the predominant structure, the basic (stair-wise) tree template was used. The layout of the first layer, a linear temporal structure, was oriented so that a left-to-right reading order would ensure that the processes be studied in chronological order. Having determined the orientation of the first layer, no freedom was left as the rest of the nodes had to be placed below the elements of the first layer. The resulting layout can be found in Figure 5.8.

**Application** The application of the 'meaningful layout' is found in using it as an access to learning environments. It should act both as an (advance) overview of the domain and as an interface to the learning environment. To explore the feasibility of the approach, SEQTool was linked to a hypertext shell.[4] The generated meaningful overview is used as main access to the hypertext fragments.

Several requirements and criteria for design were put forward (see section 5.2). A first criterion was the demand to keep the cognitive load of exploration as small as possible. A support tool should

[4]This system is a primitive shell that generates hypertext from a entity-relation-text database. The shell is also built using SWI-prolog and XPCE.

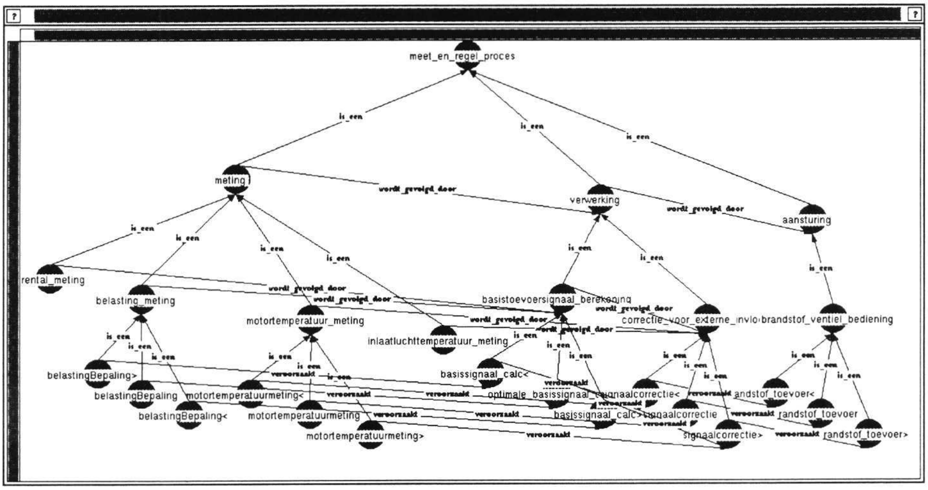



Figure 5.8: An example of a meaningful layout for a model of processes in a fuel supply system.

never distract learners from the main task. With this latter criterion in mind, the 'meaningful' visualization should not be just another tool in the hypertext environment, but should be an integral part of the environment. In the current implementation, the overview provides the only access to the underlying hypertext fragments. That is, the representation of a node in the 'meaningful layout' gives access to the underlying hypertext fragment describing that node. Thus, in the resulting hypertext system, digressions could only be made via the overview. By forcing all 'traffic' via the overview, we hoped to avoid disorientation by showing the context of each node as well as facilitating returning from digressions by revealing the path from the digression to the previously studied nodes.

## 5.5 SEQTool in the light of the requirements

In the design of support, several requirements, as put forward in chapter 2, had to be satisfied. To end this chapter with, the design solutions as realized in SEQTool will be discussed in the light of these requirements.

**Connecting to prior knowledge** For connection to prior knowledge two potential solutions were derived from the prescriptive theory as described in chapter 3. A first solution mentioned in that chapter was that of providing an *advance overview*. In SEQTool the *meaningful overview* was proposed to fulfill this function.

A second solution was that of *iterative cumulation*. As was stated in chapter 3, realization of cumulation is frequently sought in imposing a generalization-specification structure upon the original domain structure (see section 3.4.1) and in letting this structure act as rationale for a general-to-specific sequence. In SEQTool this solution was adopted. Once a subject matter structure has been modeled so that the generalization-specification structure is the predominant structure, the meaningful layout generated by SEQTool is assumed to give rise to exploration in a general-to-specific 'natural' order. The necessity to impose a generalization-specification structure upon the domain has as consequence that iterative cumulation is to be anticipated in the phase of subject matter modeling (cf., van der Hulst, 1990). All in all, the meaningful overview is to act as an advance overview as well as it should facilitate iterative cumulation by means of providing non-directive support for general-to-specific information space exploration.

**Tailored rationales** In chapter 4 we presented the following prescription: "To convey with the requirement of tailored rationales, at a fine-grained level, domain and learning-related structures must be reflected in the rationale choice and thus in the sequence." In SEQTool, essentially each structure detected should be made to act as rationale. However, within compound structures, compromises have to be made and this implies that not all structures can actually be used as rationale for sequencing. In the example, the causal structures are not taken into regard in determining the orientation of the templates in the overview.

**Structure-relatedness** A related requirement was that of structure-relatedness of exploratory behavior. In chapter 4 we presented a prescriptive model of what was called 'structure-related exploration'. This model was derived from conventions in discourse and a study of sequences in written instructional material. The model prescribes following a natural direction, which implies being consistent in direction which again implies connectivity. To support structure-related exploration, a technique for the 'meaningful' layout of graphical overviews was proposed in this chapter. Essentially this meaningful layout is constructed using visualization templates that have been defined for two primitive structure forms.

We have argued that these templates are natural representations for the internal structure, that they comply with diagram conventions. A natural mapping should facilitate interpretation of the representation and thereby enhance information preservation and processing. In addition, we have provided some evidence for the claim that these templates are likely to lead to connectivity and consistency of direction. Natural direction of exploration is achieved by manipulation of the orientation of the linear template. This template is to be manipulated so that 'conventional' left-to-right reading will guarantee a natural direction. Certainly, the above stated claims are restricted to compound structures that are limited in scope.

**Non-directive support** A last but not least important requirement was that support should be non-directive. It should provide guidance but leave control in the hands of the learner. It is this criterion that is met with providing a graphical overview that gives access to all hypertext fragments present. It principally allows for learner control, while it is supposed to provoke structure-related exploration. Whether the deliberate use of conventions would indeed lead to structure-related behavior was studied in the experiment described in the next chapter.

In the previous sections, various claims have been made about the effects of visualization, of layout manipulation of that visualization on information space exploration. In addition, claims have been made on the relation between information space exploration and the acquisition of knowledge of structure. The following chapter describes an experiment in which the major claims have been investigated.

# Experiment: Effects of layout manipulation on exploration and learning

# 6

## 6.1 Introduction

This chapter describes an experiment that was set up to assess the validity of the claims put forward in the previous chapters. To provide an overview of the claims and the relations between them, we have reproduced Figure 5.1 and specialized it to reflect the ideas proposed in chapter 5.

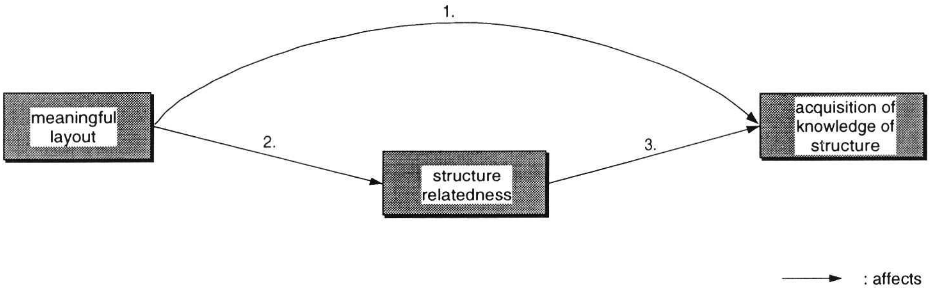



Figure 6.1: Overview of the claims as presented in the previous chapters

As Figure 6.1 illustrates, the following relations were postulated:

- A non-directive form of support, named 'meaningful layout' should affect the acquisition of knowledge of structure in two ways. The layout is assumed to convey meaning in its own right (Relation 1) and in addition, to lead to more structure-related behavior (Relation 2).
- Structure-related information space exploration was expected to give rise to an enhanced acquisition of knowledge of structure (Relation 3).

## 6.2 Experimental set-up

To assess the validity of the claims, a hypertext system was developed with three different interfaces. These different interfaces allowed us to manipulate the presence of a meaningful layout as well as the structure-relatedness of exploration.

The conditions were the following (see Figure 6.2):

- **Condition 1 (layout)** In the 'layout' condition, the overview was organized using a *'meaningful layout'*, as shown in the upper screen in Figure 6.3. The meaningful layout used in this experiment was described as an illustration in section 5.4.4.

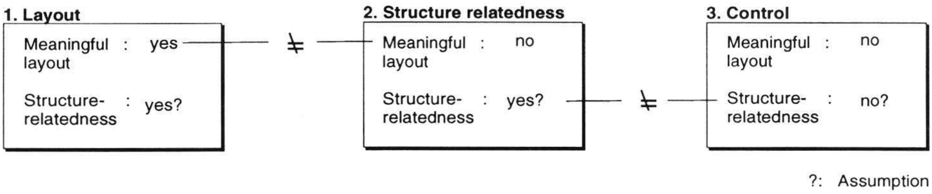



Figure 6.2: An overview of the experimental conditions

- **Condition 2 (structure-related)** The second condition (named 'structure-related') *lacked the meaningful layout.* For this condition a 'chaotic' overview was created by positioning the topics randomly on the screen and subsequentially distributing the topics so that no topic would be hidden fully by others, see the lower screen in Figure 6.3. In this condition subjects were supported to traverse the hypertext in a *'structure-related'* order. To this end, they were provided with hints on the most appropriate way to traverse the system. These hints were implemented by highlighting topics in the overview, where the order of highlighting was determined by a predefined structure-related trajectory.[1] This trajectory was fully connective, consistent of direction, and followed a natural direction where these had been defined.[2]

  It should be noted that the subjects were autonomous in their choice of exploratory trajectory. It is therefore not said that the trajectories chosen in condition 1 would be equal to the ones in condition 2.

- **Condition 3 (control)** The third (control) condition was created by using exactly the same 'chaotic' overview as was used in condition 2 and in this case no hints were provided.

The results of layout, structure-related and control condition have to be compared to test the hypotheses outlined in Figure 6.1. The numbers in that figure refer to the hypotheses mentioned below.

- When comparing the layout and structure-related condition, assuming that the resulting structure-relatedness of exploration would not differ substantially, the only difference would be the layout of visualization. The meaningful layout is expected to promote a better acquisition of knowledge of structure (Hypothesis 1).

- When comparing the layout and control condition, we expected to find more structure-related behavior for the layout condition (Hypothesis 2).

- When comparing the structure-related and control condition, under the assumption that the structure-related condition leads to more structure-related behavior, the structure-related condition was expected to lead to better acquisition of knowledge of structure within the structure-related condition (Hypothesis 3).

- Finally, when comparing the overall effects of layout with those of both structure-related and control condition, we expected the results of the layout group to be better due to an accumulation of the beneficial effects of both the visualization and enhanced structure-relatedness (the accumulation hypothesis).

[1]Since not for all primitive structures a natural direction has been defined, multiple structure-related trajectories are possible. Hence, as long as a structure was traversed in a consistent manner, the direction choice should not matter.

[2]For a specification of natural directions in the experimental domain see section 6.3.2.

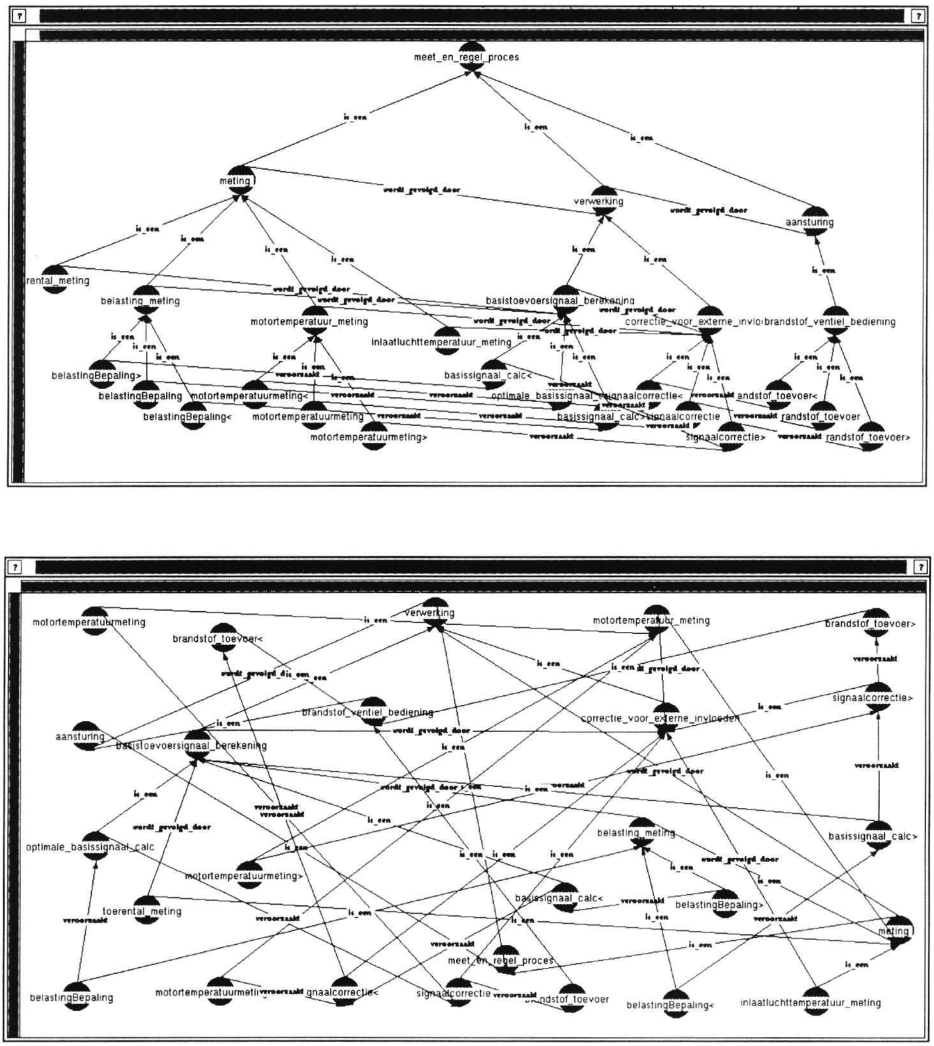



Figure 6.3: On top the 'meaningful' layout, below the 'chaotic' layout as used in the structure-related and control condition

### 6.2.1 The hypertext system

All subjects used the same hypertext system, but interfaces differed among conditions. This hypertext system consisted of 26 hypertext fragments in the domain of fuel supply systems. Since our aim was to study the influence on learning of a structure-related form of information space exploration, we decided to provide as little textual information concerning relations as possible. Therefore, great care was taken to avoid explicit references within text fragments to other topics. Hence, the only information on relations was provided by the visualization of those relations in the graphical overview. This visualization was the only access to the hypertext fragments and thus, though unusual, it was not possible to go from within one hypertext fragment directly to the other. Finally, in the interface the students were allowed to move the nodes, mainly since moving usually made relations between nodes more evident.

It should be noted that in all conditions subjects were fully *autonomous* to decide on the order of exploration.

### 6.2.2 The subject matter material

In the choice of the subject matter for this experiment, the prior knowledge of the student was a crucial factor. From the work of Lodewijks (1983) it can be learned that the effectiveness of support depends on the amount and nature of the learner's prior knowledge. Lodewijks' experiments with learner determined versus teacher determined sequences made clear that if learners possess a substantial amount of prior knowledge, teacher determined sequences may easily interfere with the individual knowledge acquisition and prior knowledge structure. This suggests that support is most likely to have effect with subject matter material that is relatively unfamiliar to the student. To prevent interference, it was decided to work with a domain that was assumed to be relatively unfamiliar to the student. This domain was the fuel supply system of a Dutch automobile. A detailed description of this domain can be found in (van der Hulst, 1990).

### 6.2.3 Subjects

The subjects ($N = 46$; 15 in the layout condition, 15 in the structure-related condition and 16 in the control condition) were first year undergraduates in psychology. Participation in the experiment was part of a study requirement, though subjects had the right to choose from several experiments. The subjects were assigned randomly to the conditions, with the exception that both genders were equally distributed over condition.

### 6.2.4 Procedure

Prior to working with the hypertext system, the subjects were trained with a four concept practice domain. While working with the hypertext system, the subjects were only told to try to learn as much as possible from the hypertext, where an above moderate performance on the posttest would be rewarded with a book token. The subjects were instructed to work at least 25 minutes with the hypertext and no maximum time limit was set. All text fragments should be read and each fragment could be read more than once. Differences in efficiency between conditions could emerge since the total time was not limited and we allowed subjects to visit text fragments more than once. To get a clear picture of the exploratory trajectory, subjects were forced to read only one fragment at a time. Finally, three types of knowledge tests as described in 6.3.1 were administered at two points in time: prior to and after the session with the hypertext.

## 6.3 Data collection

### 6.3.1 Product measures

In chapter 5 it was claimed that differences in the order of presentation would solely affect the acquisition of knowledge of structure (section 5.3.3). To find out whether indeed a differential effect could be found, we made a distinction between knowledge of concepts (definitional knowledge), and knowledge of relations (structural knowledge).

Yet another distinction should be made. With support for structure-relatedness and connectivity as main variables, we expected benefits with respect to knowledge of relations among connected concepts. The visualization was also expected to enhance the acquisition of knowledge of structure, but here we did not necessarily expect just a gain in knowledge of direct relations (i.e., relations between connected concepts). The effect of a visualization was expected in enhanced acquisition of knowledge of the overall structure. In section 5.3.1 the potential benefits of visualizations were sketched. Mainly *processing advantages* and *information preservation* were mentioned. Processing advantages only show if knowledge is required of the relation between relatively distant concepts. Hence, to see effects we should not focus on connective relations. The second aspect, 'information preservation' is certainly not restricted to connective relations. Whereas neatly ordered text may be suitable to convey knowledge of connective relations, visualizations are supposed to preserve information on overall structure. Hence, to allow differential effects of structure-relatedness respectively visualization to show, two types of tests for knowledge of structure were provided. First, a test for knowledge of single direct relations, or 'propositional' knowledge and second, a test for knowledge of the overall structure, or 'configural' knowledge (cf., Goldsmith *et al.*, 1991).

#### 6.3.1.1 Definitional knowledge

Definitional knowledge was operationalized as knowledge of concepts to be acquired from the text fragments. This type of knowledge was tested by means of a multiple choice test that required reproduction of facts as given in the text fragments that described those concepts. An example item is depicted in Figure 6.4. Pretest and posttest test consisted of a total of 20 items with 5 possible answers. The final answer option was in all cases 'no idea', this option was added since we anticipated little knowledge of the subject matter, especially in the pretest. By instructing the subjects not to guess but to use this option we hoped to avoid too large a bias due to guessing.

#### 6.3.1.2 Propositional knowledge

Propositional knowledge was tested by means of multiple choice questions. When testing a hierarchical (i.e., generalization-specification) relation we asked for categorization using inheritance of features, or for identification of subclasses. Temporal relations were tested by asking for ordering in time, or by asking for the missing parts of a procedure. Causal relations were tested by asking for predictions. All concepts and propositions that were present in the hypertext system (except for the absolutely trivial ones) were tested in the multiple choice tests. Example items for propositional

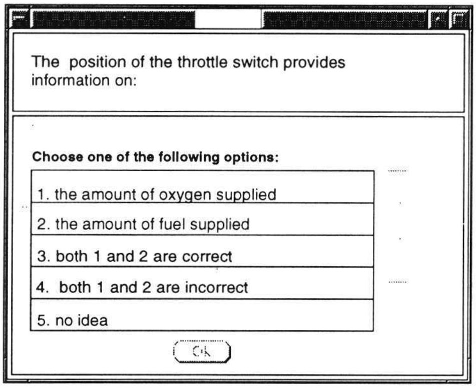
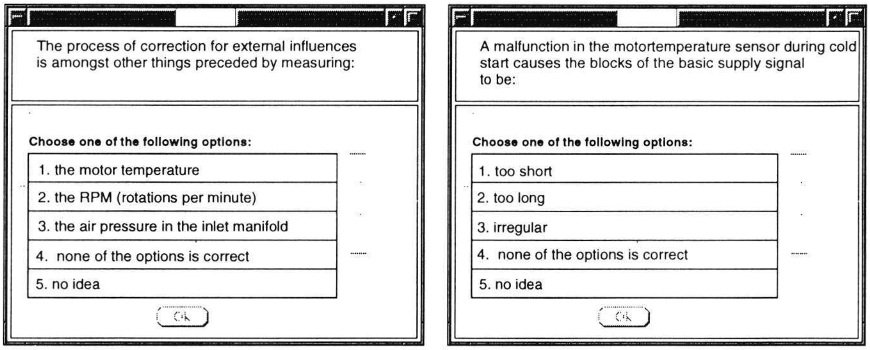



Figure 6.4: An example of a test item for definitional knowledge (translated from Dutch)

knowledge are given in Figure 6.5. Pre-test and posttest consisted of a total of 20 items, each with 5 answer alternatives, where again one of the options was the 'no idea' option.




temporal relation causal relation

Figure 6.5: Examples of test items for propositional knowledge (translated from Dutch)

#### 6.3.1.3 Configural knowledge

Configural knowledge was tested by means of a cardsort task (see Shavelson & Stanton, 1975). To obtain a measure for knowledge of the overall structure the results of each subjects cardsort task were compared with a norm model. This norm model was chosen so that it resembled the original domain organization as much as possible. That is, all primitive structures acted as clusters, except for the hierarchical structure since this structure encapsulates all other primitive structures.

In this cardsort task, the subjects were instructed to cluster the 26 topics of the hypertext. For this task a tool was created with an interface identical to that of the hypertext system, except that it did not allow access to the hypertext fragments. Subjects were instructed to move the topics to form stacks that were clusters of related topics. Neither clustering criteria nor limit on cluster-size were given.

To calculate the correspondence to the norm clustering, a proximity matrix was generated from both the subject and the norm clustering. A cell of the proximity matrix is filled with a 1 if row and column concepts belonged to the same cluster, and with 0 if they belonged to different clusters. The correspondence of the subjects' proximity matrix to the norm matrix was calculated using a measure for correspondence by de Jong and Ferguson-Hessler, as discussed in (de Jong & Ferguson-Hessler, 1986). This measure accepts matrices composed of dichotomous data as input.

### 6.3.2 Process measures

**Connectivity** As in the analysis of written material of chapter 4, sequence was described in terms of 'traverses' through a network. For the calculation of connectivity of these traverses, the measures for biased and unbiased connectivity as described in section 4.6.2.2 were used.

**Consistency of direction** A next process measure was expected to yield insight into consistency of direction within primitive structures. It should be noted that the principles of consistency of direction and natural direction only apply within the boundaries of the primitive structures (see 5.4.4). Therefore, consistency of direction and also 'natural direction' was calculated for each separate primitive structure. The primitive structures of the fuel injection domain can be found in Figure 6.6.

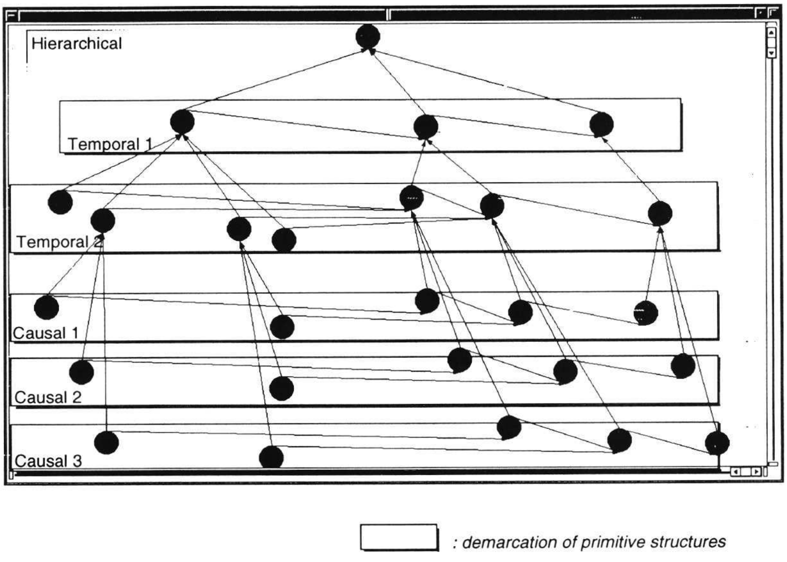



Figure 6.6: The primitive structures of the fuel injection domain

For the analysis of consistency of direction, the measure for direction preference as described in section 4.6.2.1 was applied.

The measure for direction preference required a description of the subject's exploratory trajectory in terms of forward or backward traverses. These descriptions were judged against a norm for direction preference. These norms were defined for all primitive structures. Such a norm is a subjective statement on the number of forward or backward traverses that would be minimally required to accept a pattern as consistently forward or backward. If a pattern was found to satisfy the forward norm, it was rated with a 1 and with a -1 if it satisfied the backward norm. The remaining patterns were rated zero. By this, a measure for direction preference was achieved. For consistency of direction the absolute value of direction preference was used.

Table 6.1 lists the minimum number of traverses in a certain direction that had to be found to accept the pattern as consistent in that direction. In the table, $F$ stands for the number of forward traverses within a pattern and $B$ for the number of backward traverses within a pattern.

Table 6.1: Norm for direction preference per primitive structure

| *Structure type* | *Direction* | |
|---|---|---|
| *(total number of relations)* | *Forward* | *Backward* |
| hierarchical (25) | $F > 16$ | $B > 18$ |
| temporal-1 (2) | $F = 2$ | $B = 2$ |
| temporal-2 (6) | $F \geq 5$ | $B \geq 6$ |
| causal (all) (4) | $F = 4$ | $B = 4$ |

**The norm** The norm patterns above have been established considering the following. In earlier work (see chapter 4) we applied a binomial measure to assess whether a pattern of forward and backward traverses showed a consistent preference in either direction. A norm for direction preference was obtained by calculating (on the basis of a binomial distribution) the minimal number of forward traverses for which the assumption of no direction preference would be violated (see section 4.6.2.1).

However, a drawback of this measure is that it requires a minimal number of 5 traverses within a pattern to be sufficiently powerful (at $\alpha = .05$). The number of relations within the primitive structures used in the current experiment, and consequently the number of potential traverses is in most cases very limited. For instance, within temporal-1 only two potential traverses were possible. All in all, only for the hierarchy and temporal-2 could a norm be set using the binomial distribution.

To allow a rating for patterns in which the number of potential traverses is small, it was necessary to set a more subjective norm. Hence, for structures with 4 or fewer potential traverses, it was decided that if all potential traverses were in the same direction, the trajectory would be accepted to be consistent of direction. With this, we have accepted a relatively large type I error. That is, for instance, the probability of the outcome of two forward traverses in temporal-1 due to chance would be .25 and thus relatively high.

Finally, within branched structures the norm for forward patterns was reduced by 10% since some forward patterns in branched structures would not lead to a maximal score.

**Secondary analysis** A stringent norm was used for a secondary analysis of consistency of direction. This norm required at least half of the minimal number of traverses to be connective. This second norm was introduced to make a distinction between deliberately chosen consistency within a structure, and consistency of direction that resulted from choices made in related structures. Only the first kind of consistency is characterized by connectivity within a structure.

**'Natural' direction** Consistency of direction was expressed using the absolute value for the measure for direction preference. The real value for this measure is used to gain insight into the direction preference of subjects within each of the primitive structures. A result of -1 would indicate an absolute preference for a backward direction, a 1 for a forward direction whereas a result that approached 0 suggested lack of direction preference.

The direction preferences found are matched to the 'natural' directions defined for some of the structures. The natural directions are:

- **hierarchy:** backward, that is general-to-specific;
- **temporal-1:** forward, that is chronological;
- **temporal-2:** undefined, generally a forward, chronological sequence is seen as the natural direction for temporal structures, however, temporal-2 is branched and for branched structures a backward, root-leaf direction convention exists;
- **causal-1,2,3:** undefined, no natural direction was defined for causal structures.

**Overall activity and time** Exploratory learning is known to be time consuming. To detect differences in efficiency amongst the conditions, time on task and activity was measured. Activity is expressed in terms of the total number of traverses made by the subject.

## 6.4 Results

### 6.4.1 Overall activity and time

Analysis of variance revealed no differences between conditions for time on task ($F(2,43) = 2.49$, ns). The mean duration in seconds for the layout group was 1691 ($SD = 253$), for the structure-related group 1990 ($SD = 439$) and for the control group 1833 ($SD = 482$). Activity in terms of the number of traverses also shows no differences ($F(2,43) = .85$, ns). The mean number of traverses in the layout group was 41.60 ($SD = 12.62$), 35.13 ($SD = 16.03$) in the structure-related group, and 43.56 ($SD = 24.76$) in the control group. No correlation was found between time on task and the dependent variables; propositional knowledge ($r = -.03$) or configural knowledge ($r = .02$).

During a qualitative analysis of the exploratory trajectories of the 3 best and 3 worst performers[3] of both the layout and control group, it was observed that the difference between activity by the best and worst performers was quite large, not in terms of time on task but in terms of the number of traverses made. However, for the whole population of the two conditions, no correlation was found between the number of traverses and propositional knowledge ($r = .17$) or configural knowledge ($r = .14$).

### 6.4.2 Product measures

In Figure 6.7 we have schematized the outcomes of the product measures. The results of the test for definitional and propositional knowledge are expressed in terms of the number of items correct (out

[3] A judgment of performance was based on extreme scores on the test for propositional knowledge. Mean scores of the best performers were 15.5 (layout) and 12 (control) items correct out of a total of 20, versus 6 (layout) and 3 (control) for the worst performers.

of 20), whereas configural knowledge is expressed in terms of correspondence to a norm model. For the data on configural knowledge, due to lack of activity in the cardsort task, the results of 1 subject from the layout condition and that of 1 subject from the structure-related condition had to be removed from the data set (N=44).

The results can also be found in Table 6.2.

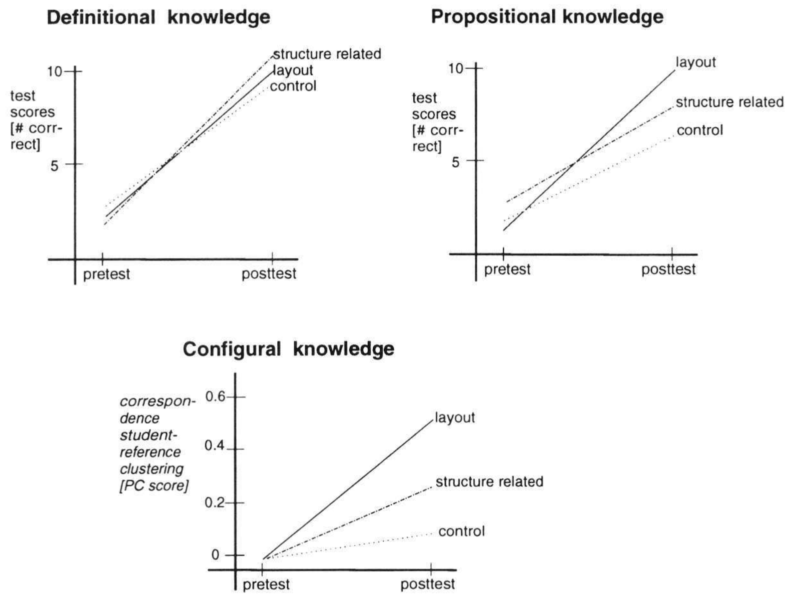



Figure 6.7: Results of the measures for definitional, propositional, and configural knowledge respectively

As can be seen in Figure 6.7, no large differences in prior knowledge were found. Indeed, one way multivariate analysis of variance does not reveal a difference between conditions ($F(6,80) = 1.20$, ns.) for the pretest results. Univariate analysis of these results reveals no significant differences between conditions for either of the dependent variables; definitional knowledge ($F(2,42) = .31$, ns.), propositional knowledge ($F(2,42) = 1.3$, ns.) and configural knowledge ($F(2,42) = .01$, $ns.$). Although the pretest differences for propositional knowledge are small, disregarding these may lead to inappropriate conclusions. Hence, from here on we will use 'knowledge gain' scores that reflect the differences between pretest and posttest scores.

These knowledge gain scores, when subjected to a multivariate analysis, showed an overall constant effect, indicating that the subjects indeed learned from working with the hypertext environment ($F(3,41) = 64.87$, $p < .00$). This learning effect was significant for definitional knowledge gain ($F(1,43) = 167.25$, $p < .00$), propositional ($F(1,43) = 122.30$, $p < .00$) and configural knowledge gain ($F(1,43) = 31.56$, $p < .00$).

The different treatments were found to affect learning since the gain scores showed a main effect of condition ($F(6,78) = 3.76$, $p < .00$). Using a univariate analysis, this main effect can be ascribed to effects on propositional and configural knowledge. For these types of knowledge gain, the results revealed significant differences between the conditions ($F(2, 41) = 7.46$, $p < .00$) and ($F(2, 41) = 6.81$, $p < .00$) respectively. Univariate analysis revealed no differences for definitional knowledge ($F(2, 41) = .59$).

When analyzing the effects on propositional and configural knowledge, using a one-way univariate analysis for each of the dependent variables, a post hoc analysis (Scheffé) revealed that differences between the layout condition and the structure-related condition and differences between layout condition and control condition are significant (at $\alpha = .05$) for both the propositional knowledge and the configural knowledge test. Differences for propositional knowledge between the structure-related and the control condition were not significant. Differences for configural knowledge between the structure-related and the control condition were only marginally significant ($t = 1.67, df = 28, p < .06$).

As expected, for definitional knowledge no differences between conditions were found.

Table 6.2: Mean scores (and $SD$) on the knowledge tests

| | Definitional | | | Propositional | | | Configural | | |
|---|---|---|---|---|---|---|---|---|---|
| | *Pre* | *Post* | *Gain* | *Pre* | *Post* | *Gain* | *Pre* | *Post* | *Gain* |
| lay-out | 2.67 (2.72) | 10.00 (3.49) | 7.28 (3.85) | 1.53 (1.89) | 10.33 (3.16) | 8.08 (3.59) | -.01 (.08) | .49 (.32) | .50 (.35) |
| struc. rel. | 2.20 (2.14) | 10.33 (2.29) | 8.13 (2.95) | 2.87 (3.42) | 8.47 (2.00) | 5.60 (3.85) | -.02 (.10) | .27 (.30) | .28 (.41) |
| con-trol | 3.13 (3.05) | 9.56 (4.12) | 6.44 (4.53) | 2.06 (2.27) | 6.81 (3.19) | 4.75 (2.65) | -.02 (.07) | .08 (.23) | .10 (.22) |

### 6.4.3 Process measures

#### 6.4.3.1 Connectivity

The scores for the biased measure of connectivity are almost identical for the three conditions ($F(2, 43) = .21$) (see Table 6.3). The unbiased scores, however, show a main effect of condition ($F(2, 43) = 11, 32$, $p < .00$), where a posthoc analysis (Scheffé) reveals that unbiased connectivity scores were significantly higher for both layout and structure-related group when compared to those of the control group.

Table 6.3: Mean scores (and $SD$) for connectivity

| | *Biased* | *Unbiased* |
|---|---|---|
| layout | .53 (.04) | .90 (.04) |
| structure-related | .53 (.07) | .87 (.10) |
| control | .52 (.08) | .75 (.13) |

We may thus infer that the latter differences are not due to plain connectivity of traverses but might be due to differences in efficiency. Within the experimental condition a larger share of the non-connective steps must have been via previously visited nodes. This implies that, though large steps were made, those steps were not to unrelated topics. In contrast, subjects in the control group must have jumped more frequently to unrelated material. All in all, since it is impossible to traverse a branched structure in a connective way without returning to previously visited nodes, we may contend that subjects in the experimental condition chose a more efficient path. More than subjects in the control condition, they avoided redundancy by skipping previously visited nodes while ensuring that target nodes still had some relation to previously seen material.

During a qualitative analysis of the traverses of 12 subjects[4] from the layout and control group, we observed some striking differences between the groups in the initial exploration phase. The trajectory of the layout group was found to be highly connective right from the beginning. Large 'jumps' were only observed in a later stage of exploration. In contrast, within the control group 'jumping' was certainly seen in the initial stage. A possible explanation might be that subjects in the control group started browsing the material but that the layout and structure-related group may have skipped this phase.

If this is indeed the case, the following expectations should be met. For the control group due to 'jumping', the (unbiased) connectivity should be less during the first traverses than during subsequent traverses. In contrast, for the layout group the unbiased connectivity should be equal or even larger during the initial phase compared to that of the traverses following the initial phase. Hence, to investigate this, each trajectory was split up into an 'initial phase', incorporating the first 10 traverses and a 'final phase' incorporating the traverses 11 and on. The connectivity results for both phases can be found in Table 6.4.

Table 6.4: Mean scores (and SD) for connectivity

| | Phase | |
|---|---|---|
| | *Initial phase* | *Final phase* |
| layout | .95 (.08) | .90 (.18) |
| structure-related | .92 (.16) | .86 (.09) |
| control | .63 (.04) | .81 (.11) |

The unbiased connectivity scores for the control group are indeed significantly lower in the initial phase ($t = -5.17$, $df = 15$, $p < .00$) compared to the final phase. In addition, the unbiased connectivity scores of the layout group are significantly higher in the initial phase ($t = 2.37$, $df = 14$, $p < .02$) compared to the final phase, while the same holds (marginally) for the structure-related group ($t = 1.64$, $df = 14$, $p < .06$). While starting connective, the subjects of the layout and structure-related group 'jumped' a bit more later on, though still less than the control group ($F(2, 43) = 3.29$, $p < .05$). A posthoc analysis revealed still a significantly larger connectivity score for the layout group compared to that of the control group.

In the light of these results, the control group must have started 'jumping' through the domain and changed behavior later to a more connective way of traversing. We interpreted the 'jumping' in the initial phase as 'browsing' or even stronger, 'scanning' (McAleese, 1989) the content, where the intention is not to study the content of the hypertext fragments in detail but more to orientate upon the overall structure. The layout and structure-related group may not have needed such an orientation phase. The unbiased connectivity scores of the layout group were significantly higher

[4] The selection used here was the same as mentioned in section 6.4.1. It included the traverses from the 3 best and 3 worst performers from the layout and control group.

in the initial phase compared to the later phase. Hence, the layout group must also have changed behavior during exploration. While starting connective, they 'jumped' a bit more later on, although still less than the control group. We may conclude that differences in the exploration process with respect to connectivity are particularly large in the first phase; the control group started 'jumping' whereas the layout group worked extremely systematical. In the following–main–phase, behavior is less extreme, and thus shows more similarity between conditions.

#### 6.4.3.2 Consistency of direction

The data on consistency of direction (as can be found in Table 6.5) shows an overall effect for condition, except for the first causal structure. Analysis of variance reveals the following effects: for the hierarchy ($F(44, 2) = 45.48$, $p < .00$), temporal-1 ($F(44, 2) = 4.74$, $p < .01$), temporal-2 ($F(44, 2) = 13.81$, $p < .00$), causal-1 ($F(44, 2) = 1.70$, ns), causal-2 ($F(44, 2) = 16.52$, $p < .00$), causal-3 ($F(44, 2) = 12.25$, $p < .00$).

Post hoc analysis reveals a general pattern. The level of consistency in the layout and structure-related condition is for all structures significantly higher than in the control condition, again with the exception of the first causal structure.

Table 6.5: Mean scores (and $SD$) for consistency of direction

| | Conditions | | |
|---|---|---|---|
| *Primitive structure* | *Layout* | *Structure related* | *Control* |
| hierarchy | .93 (.26) | .88 (.34) | .06 (.25) |
| temporal-1 | .80 (.41) | .88 (.34) | .44 (.51) |
| temporal-2 | .87 (.35) | .88 (.34) | .25 (.45) |
| causal-1 | .73 (.46) | .69 (.48) | .43 (.50) |
| causal-2 | .67 (.49) | .81 (.40) | .06 (.25) |
| causal-3 | .67 (.49) | .56 (.51) | .00 (.00) |

The secondary analysis leads to a different pattern. In this analysis, we used the more stringent norm. This norm required at least half of the minimal number of one-direction traverses to be connective. Where the results within the hierarchy and temporal-1 did not differ, in particular in the causal structures a completely different outcome could be observed. In the layout conditions subjects evidently failed to comply with the more stringent norm. The results here dropped substantially, with as a consequence the structure-related group performing significantly better on consistency, compared to both layout and control.

It should be noted that the measure for consistency inherently carries the danger of not doing justice to a so called 'mountain' pattern. This is a pattern that shows a number of steps in one direction and after a breakpoint again a number of step in a reverse direction. The former mentioned consistency measure would rate this pattern as 'inconsistent'. This rating would do no justice to this pattern. Therefore, we analyzed a set of 12 trajectories on the presence of such 'mountain' patterns. As we found no evident cases, we perceived no need to correct the measure of consistency.

#### 6.4.3.3 Natural direction

To make statements with regard to the 'natural direction', firstly the question was to be addressed whether differences between conditions occurred with respect to direction preference. Subsequently, it should be assessed whether an observed direction preference was in accordance with the 'natural direction' (as defined in Section 6.3.2).

As can be seen in table 6.6, for all structures we found large main effects for condition. Analysis of variance yielded the following results: for the hierarchy ($F(44,2) = 45.48, p < .00$), temporal-1 ($F(44,2) = 13.81, p < .00$), temporal-2 ($F(44,2) = 47.64, p < .00$), causal-1 ($F(44,2) = 27.48, p < .00$), causal-2 ($F(44,2) = 55.59, p < .00$), causal-3 ($F(44,2) = 35.43, p < .00$). Post hoc analysis showed that for the hierarchy and temporal-2 structure the direction preferences within the layout and structure-related condition were equally strong. The direction preference within the control condition was significantly weaker than that of structure-related and layout condition. With respect to natural direction, the layout and structure-related group showed a clear preference for the natural direction. That is, for the hierarchy a backward and for temporal-1 a forward direction.

For the remaining structures a posthoc analysis revealed a general pattern. Consistently significant differences for layout and structure-related group were found. Where the structure-related group was supported to explore temporal-2 and causal-1, 2, and 3 in a backward way, the layout group evidently preferred a forward direction. In all cases the control group was found somewhere between the layout and structure-related group, thus showing no direction preference at all. For all structures, differences between results for layout and control group as well as for control and structure-related group were found to be significant.

Table 6.6: Mean scores (and $SD$) for direction preference

| | Conditions | | |
|---|---|---|---|
| *Primitive structure* | *Layout* | *Structure related* | *Control* |
| hierarchy | -.93 (.49) | -.88 (.26) | -.06 (.25) |
| temporal-1 | .67 (.61) | .88 (.34) | -.19 (.66) |
| temporal-2 | .87 (.35) | -.75 (.58) | -.25 (.45) |
| causal-1 | .73 (.48) | -.69 (.48) | .18 (.65) |
| causal-2 | .67 (.49) | -.81 (.40) | -.06 (.25) |
| causal-3 | .67 (.49) | -.56 (.51) | .00 (.00) |

#### 6.4.3.4 Perspective choice

All previously described process measures are indications of structure-relatedness, which is more or less an indication to which extent a subject's exploration has been structure-related. Besides being more or less structure-related, the subject's trajectory can also reveal perspective preferences. Perspective preference indicates differences in focus of attention, the question was whether different conditions gave rise to different focuses.

The subject matter used in this study principally allowed a subject to work from various perspectives. A subject might, for instance, consider the causal structures to be of major importance, focus attention on that structure and thus follow each possible causal trail and only incidentally make 'excursions' to other primitive structures. In contrast, one might descend the hierarchy without making a single connective traverse within the causal structures. Comparing both trajectories, a perspective difference might be a justified conclusion.

Perspective preference is indicated by attention focus. Attention focus on a structure is defined to be shown by a relatively large number of unbiased connective traverses within that structure. For instance, the structure-related condition was designed so that if students followed the hints, all structures would be explored in a connective manner. Each structure was kept 'in focus' for a while, allowing for a structure-related exploration of the structure, after which a shift to a next structure could take place. As we concluded before that the subjects to a large extent choose to follow the hints, the structure-related condition can be seen as a nice example of a perspective-wise form of exploration.

The results of the structure-related condition could thus act as base rates for attention focus on a structure. Hence, when for a structure the mean number of connective traverses was significantly less than the number found in the structure-related condition we could conclude that the structure of concern has never been a focus of attention in the particular condition. Table 6.7 shows the mean number of (unbiased) connective traverses per condition per primitive structure.[5]

Table 6.7: Mean number (and $SD$) of (unbiased) connective steps in a primitive structure

| | Conditions | | |
|---|---|---|---|
| Primitive structure | *Layout* | *Structure Related* | *Control* |
| hierarchy | 26.22 (2.20) | 24.19 (5.58) | 17.00 (8.03) |
| temporal-1 | 1.53 (1.06) | 1.8 (.91) | .69 (.70) |
| temporal-2 | 3.27 (2.09) | 5.9 (1.67) | 2.31 (1.45) |
| causal-1 | .40 (.73) | 2.6 (1.70) | 2.44 (1.31) |
| causal-2 | .60 (1.30) | 3.12 (1.63) | 1.75 (1.24) |
| causal-3 | .53 (.83) | 3.31 (1.74) | 2.00 (1.71) |

Post-hoc analysis reveals that in the hierarchical structure in each of the layout and structure-related conditions more connective steps were taken than in the control condition. Within temporal-1 the same pattern was found, more connective steps were taken in the layout and structure-related condition compared to the control group. Within temporal-2 the structure-related condition showed more connective steps when compared to the layout and control group.

The most spectacular differences are found in the three causal primitive structures. The number of connective traverses found in the layout condition is substantially lower than the number found in the structure-related condition, and even lower than in the control group (significant for all three causal structures). This pattern is consistent for all three causal structures and we may conclude that the meaningful layout was not supportive of a causal perspective, whereas it evidently was supportive of a hierarchical one. Figure 6.8 illustrates this by showing the differences between the mean number of connective traverses within the three causal structures and the hierarchical structure.

[5]It should be noted that for the control condition the overall mean number of traverses is smaller. Normalization for overall number of traverses would however lead to an overestimation of attention focus in the control condition.

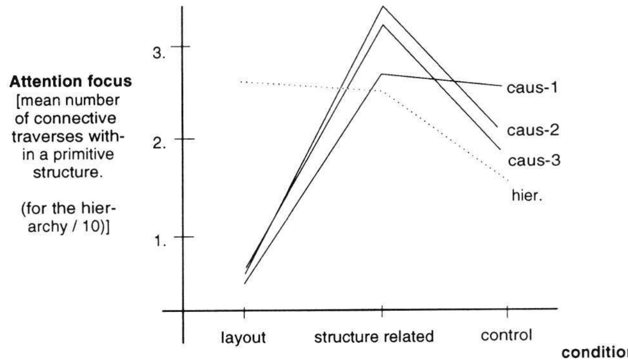



Figure 6.8: Perspective preference based on connectivity within primitive structures (for the causal and hierarchical structures)

#### 6.4.3.5 Qualitative analysis of the process

A qualitative analysis of the exploration trajectory of six subjects from each of the three conditions revealed a number of differences in the exploratory pattern. The trajectories selected for qualitative analysis were those of the three best and three worst performers within a condition (see also section 6.4.1).

The use of a reading metaphor was evident especially in the behavior of the subjects of the control group. After analyzing the control group on starting point, we found that 81%[6] of the subjects in this group chose to start at the topic in the upper left hand corner, where none of the subjects in the layout group chose to start at this topic. A 73% of these subjects started at the root node of the predominant hierarchical structure.

In the structure-related condition, the reading metaphor was evidently less important as guiding principle. Analysis of the exploratory trajectory of the subjects in this condition showed that the subjects initially followed the suggested trajectory and thus started at the root node of the predominant hierarchical structure. It should be noted that the suggested order by no means follows a reading direction. Deviations from the suggested trajectory were mainly found in the later stadia.

A final finding relates to differences between best and worst performers. Two of the well performing subjects from the layout group appeared to have chosen a 'viewpoint-wise' exploration. Like most of the other subjects they started with descending the hierarchy and did not explore the layers in a connective way. Later on though, they returned to the bottom layers and traversed these layers again, following the links of the temporal or causal structures. None of the bad performers showed similar behavior. Viewpoint-wise exploration might be an indication of an effective trajectory. This speculation demands further study, since, if valid, it might be a start to further improvement of support for exploratory learning.

### 6.4.4 Structure-relatedness as predictor for achievement

An important question is to which extent enhanced acquisition of knowledge of structure could have been due to structure-related exploration. To gain a first impression, a Pearsons' product-

[6]This data is based on an analysis of exploratory pattern of all subjects within a group

moment correlational analysis was performed on the relation among process and product measures.

As was concluded that the students in the structure-related group largely followed the suggested trajectory, no correlations between process and product measures could be expected. An analysis of correlations for the structure-related condition confirmed this expectation. For the control condition a similar analysis revealed no significant correlations. In contrast, for the layout group several significant correlations were found. In Table 6.8 correlations are provided for the layout group only. The table shows correlations between the gain scores for definitional, propositional and configural knowledge, and measures for unbiased connectivity, consistency of direction and for direction preference for the two structures, hierarchy and temporal-1, for which a natural direction was defined.

Table 6.8: Correlations of process — product measures (for the layout group only)

| | Product measure | | |
|---|---|---|---|
| *Process measure* | *Definitional* | *Propositional* | *Configural* |
| **Unbiased connectivity** | | | |
| | .15 | .35 | .12 |
| **Consistency** | | | |
| hierarchy | -.47 | -.40 | -.03 |
| temporal-1 | -.04 | -.17 | .27 |
| temporal-2 | .19 | .54* | -.30 |
| causal-1 | .45 | .36 | .57* |
| causal-2 | .40 | .57* | .35 |
| causal-3 | .40 | .49 | .78** |
| **Direction preference** | | | |
| hierarchy$^{\alpha}$ | .47 | .40 | .03 |
| temporal-1 | .34 | .06 | .33 |

*: significant at $\alpha = .05$

**: significant at $\alpha = .01$

$^{\alpha}$ Direction preference in the hierarchy was originally found to be negative (i.e. indicating a preference for a backward direction). However, absolute values were used for calculation of correlations

The results provide support for the expectation of differential effects of structure-relatedness of exploration on the acquisition of knowledge of definitions and knowledge of structure respectively. Correlations between structure-relatedness and structural knowledge gain are found frequently. In contrast, no correlation is found for structure-relatedness and definitional knowledge gain.

## 6.5 Conclusions

With respect to the validity of the hypotheses we refer to Figure 6.9 that was first presented in section 5.3.

**Hypothesis 1** The first hypothesis was "The use of a meaningful layout by itself gives rise to a better acquisition of knowledge of structure apart from effects that can be accounted for by

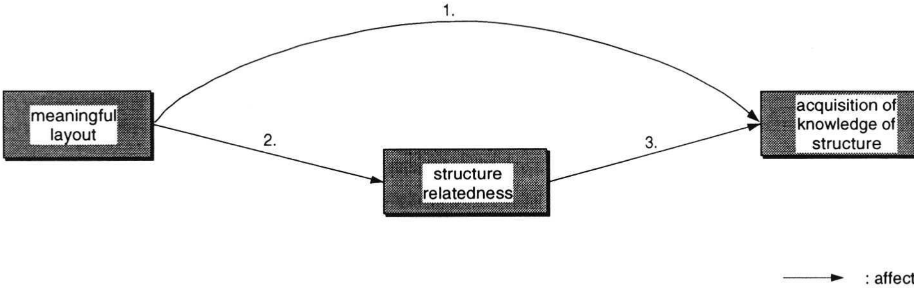



Figure 6.9: Overview of the hypotheses

structure-relatedness of exploration". With respect to this hypothesis, first of all, we should point at a comparison of results of the layout and structure-related conditions. The assumption here was that both conditions would lead to an approximately similar form of structure-related exploration. The data presented in section 6.4.3 suggests that this assumption was not violated. Therefore, the main difference between these conditions was the layout of the graphical overview. Hence, effects found should be due to differences in visualization. Indeed, as reported in section 6.4.2, for both propositional and configural knowledge, significant differences were found between the layout and structure-related condition. Hence, we may conclude that the meaningful layout for this domain conveyed meaning in its own right. A second conclusion can be that the effect of the visualization lies in acquisition of knowledge of structure, as no differences were detected amongst definitional knowledge gain.

Similar differential effects were found when comparing the layout and control condition. Again, no differences for definitional knowledge gain were found, whereas substantial differences for both types of structural knowledge gain emerged.

**Hypothesis 2** The second hypothesis was "The use of a meaningful layout leads to more structure-related exploration". This hypothesis was not rejected.

To assess the validity of the hypothesis, the exploratory behavior found in the layout and the control condition had to be compared. When considering unbiased connectivity we can conclude that the layout group did significantly better. A similar finding was reported for consistency of direction: 5 out of 6 primitive structures were found to be traversed more consistently by the layout group. Finally, for those structures for which a natural direction was defined, the hierarchy and temporal-1, the layout group showed a stronger preference for a natural direction than did the control group. Only a single exception amongst 9 hits in our view justifies the claim that the meaningful layout promoted more structure-related behavior.

**Hypothesis 3** The third and final hypothesis was "Structure related behavior results in a better acquisition of knowledge of structure". Correlational analysis for the layout group reveals several significant correlations between consistency of direction and gain of propositional and configural knowledge, whereas for definitional knowledge no such correlations were found. This data suggests that at least some relation exists between structure-relatedness and gain of propositional and configural knowledge.

In addition, one should consider differences in knowledge gain between the structure-related and control condition. These conditions could be compared on differential effects with respect to structural knowledge gain under the assumption that the structure-related group explored in a more structure-related way. Analysis of structure-relatedness as reflected in the process measures shows that this assumption is valid. Study of the trajectories in both conditions revealed significant differences with respect to unbiased connectivity. A similar finding with respect to consistency of direction was reported for 5 out 6 primitive structures. For natural direction, differences were significant for all structures. This indeed justifies the assumption that the structure-related group explored in a more structure-related way than did the control group.

When thus comparing the results of the structure-related group and the control group, the test for propositional knowledge did not reveal any differences and the differences found for configural knowledge were only marginally significant. This data thus does not provide firm evidence to the hypothesis stating that "structure-related behavior results in a better acquisition of knowledge of structure".

This final statement has implications that should get the attention they deserve. In this thesis, the importance of a structure-related information space exploration for acquisition of knowledge of structure was postulated. However, the data indicates that structure-relatedness of information space exploration might be less important than was assumed, or that structure-relatedness alone is not sufficient to result in an enhanced acquisition of structure.

## 6.6 Discussion

It can certainly be doubted whether plain hypertext environments are an appropriate means for learning. The learning of large amounts of unfamiliar material demands a type of support that is usually not available in today's hypertext environments. Learners themselves demand for more support, referring to a study by Allison and Hammond (1989) who compared different navigation tools, among which guided tours and graphical overviews. The main conclusion from this study was that learner preference for navigation guidance was highly related to the nature of the task, that is searching, browsing, or learning of (un)familiar material. As Allison concluded, for learning unfamiliar material, the guided tour was certainly preferred over the plain graphical overview. This guided tour is not too far from the 'good' book that is prefered by so many over hypertext environments. However, we should not reject hypertext too readily as a medium for learning.

With the rapid evolution of the World Wide Web enormous amounts of hypermedia material will become widely available. Most of the material will be tailored to information retrieval. Yet, a growing body of instructional material will appear on the internet or on private sites (cf., Barnard & Sandberg, 1994). Through putting the material on the Web, learners with different backgrounds and goals are reached. No single good book might serve all the needs of this highly varied group of learners. Plain hypertext will not be very effective either. Hypertext principally provides the flexibility needed to serve learners with different needs. But, to enable them to make effective use of this flexibility, they should be provided with the cognitive tools that allow them to regulate their own learning.

Plain graphical overviews are not very effective in supporting navigation. The overview used in the structure-related and control condition certainly was not created just to give the students a hard time. It was highly similar to overviews used in systems such as NoteCards (see an example of NoteCards' global overview in (Conklin, 1987)). As our study suggests, the positive effects of visualization can still be enhanced. Zhao et al. (1993) already showed that visualization of relations actually enhances the acquisition of knowledge of structure. The experiment reported here has shown that the impact of visualization of relations can even be improved by visualizing the overall structure by means of a well designed layout. From the present experiment, it could be concluded that a 'meaningful overview' might convey meaning in its own right. In addition, such an overview tailored to comply with diagram and reading conventions can result in more methodic exploration. This experiment, however, provided no strond evidence for positive effects of such methodic information space exploration.

The meaningful layout technique might be one small step in the right direction, but many problems are unsolved. The idea was to provide learners with an overview that both revealed the internal structure of the domain and that in a 'natural' way promoted structure-related behavior. For a single, small and relatively well structured domain an obvious positive effect could be observed. The fuel-injection domain was so small that it could be shown entirely, but what to do with larger structures? Zooming in could be one solution, but might lead to lack of overview.

Also, the nesting of visualizations of structures is a problem only very partially explored in this work. The present algorithm only facilitated the nesting of two structures. Nesting of more complex structures will no doubt lead to conflicting demands.

A next problem is due to the nature of conventions, as Winn (1983) remarks, conventions are used if no other guiding principle exists. Say, for instance, learners are supposed to study aspects of several countries among which is their native country. Undoubtedly, those learners will tend to start off with their native country, irrespective of its position on the screen. In this case support based on reading direction conventions will fail. In studying the effects of the meaningful layout one should get a clear picture of the question when diagram conventions prevail and when other principles overrule those conventions.

One more thing should be noted. The hypertext system that was used in this experiment was far from realistic. It lacked so called 'organizational' links, such as 'go back', 'go to the home page'; and 'textual' links, such as 'annotation', 'definition', and 'explanation' links (see Zhao *et al.*, 1993). A hypertext system may contain numerous links, many of which are rather local. In our view, a hypertext system should be hybrid. That is, text fragments should give direct access to local textual links, text frames should give access to organizational links, and all domain-related links (the 'referential' links as to Zhao et al.) should be present in an overview containing a meaningful visualization of domain structure.[7]

Given the above noted shortcomings, the meaningful layout algorithm should be subject to further development and experimentation. After such further development, the algorithm might find its application as an extension to WWW browsers. To automatically generate meaningful overviews, it should be possible to reconstruct domain structure from, for instance, a HTML representation of hypermedia material. The present generation HTML does not readily allow this. The links in HTML are untyped and this makes it impossible to make distinctions between, for instance, textual, organizational and referential links. However, one of the research advances in the hypermedia field is work on typology of links (see e.g., Bloomfield, 1995). In the near future, HTML may be extended with facilities for typed links. It is likely that, with typed links, it will at least be possible to make a distinction between textual, organizational, and referential links. Meaningful layout, however, in addition requires a standardized typology of referential links. For such a standardized typology to emerge, patience will be a virtue.

[7]The hypertext that was used in the experiment described here did not contain any of those 'organizational' or 'textual' references.

# Part C

The chapters 4, 5, and 6 were dedicated to the development of support for information space exploration in a hypertext environment. In chapter 4 we described the development of a prescriptive model (SEQModel). Chapter 5 described techniques for non-directive support based on SEQModel, implemented in an authoring system (SEQTool). Chapter 6 documented an experimental study that aimed at assessing the effects of an application of the support generated by SEQTool.

Part C, the chapters 7, 8, and 9, describes highly similar activities, that are, however, directed at simulation-based learning environments. The starting points of part B and C were different, SEQModel had to be built from scratch and chapter 4 was thus dedicated to model development. For part C we adopted a currently available prescriptive model, the Model Progression approach as originally described by White and Frederiksen. Chapter 7 is thus dedicated to tailoring the Model Progression approach to make it more generally applicable. A second aim is to make the approach more operational for use in an authoring tool. The resulting model (MPModel) is used as a basis for an authoring tool (MPTool). Chapter 8 describes the authoring tool together with an evaluation of the tool and its underlying MPModel. Chapter 9 describes an experimental study that aimed at assessing the effects of support based on MPModel.

# Model Progression: generalization and operationalization

# 7

## 7.1 Introduction

The problem tackled in this chapter is that of tailoring White and Frederiksen's Model Progression approach (1988; 1989; 1990) for use in a model based authoring tool (to be labeled MPTool hereafter). This MPTool was to be part of the SMISLE authoring system for simulation-based learning environments (see section 1.4). SMISLE provides authors with tools for the development of simulation environments for exploratory learning, combined with so called 'measures' that aim at supporting the process of exploration and discovery. Model Progression (MP) is one of these measures. The intention was to integrate in SMISLE an authoring tool that would provide both technical and conceptual support for the construction of MP. The tool should help authors to build their simulations as a series of MP 'levels' that gradually progress in complexity and concurrently provide various perspectives on the simulated phenomena.

In the following section we will briefly review the motives for adopting MP as a means for support of exploratory learning in simulations.

### 7.1.1 Information space exploration: a demanding task

Would one ever consider to put an aspirant pilot without any prior training in a flight simulator and confront this pilot with the full complexity of navigating, course planning, trouble shooting etc? In the world of training simulators it is generally accepted practice (see e.g., Kuiper, 1995) to organize training by means of a series of training scenario's. Initial scenario's confront the learner with very simple part-tasks in usually restricted environments. The scenario's then gradually progress toward the most complex situations a trainee may ever have to face, generally that of dealing with emergencies.

In the world of conceptual simulations, simulations that incorporate models of causal phenomena, the use of such scenario's has been less prevalent. The essence of the application of exploratory learning environments such as conceptual simulations, is that of getting learners more actively involved in the learning process. As was argued in chapter 1, the gain of active involvement was assumed to be the acquisition of a deeper understanding of the simulated phenomena. As a consequence, more freedom is generally granted than is common in training simulators.

However, the practice of conceptual simulation-based learning shows that the learner's own activity is not always beneficial. With respect to learning with simulations, multiple studies report highly unmethodic exploration. Such exploration manifests itself, for instance, in changing multiple variables concurrently (Shute & Glaser, 1990; Veenman, 1993; Kamsteeg, 1994) or in aimlessly 'browsing' through the simulation environment (Shute & Glaser, 1990). This 'floundering' (Goodyear *et al.*, 1991) is not likely to be accompanied by effective learning (Veenman, 1993).

In unsupported simulations, students readily start investigating complex relations, the understanding of which requires an awareness of relations elsewhere in the model. Referring to the domain of oscillation that we will use throughout this study as illustration, students might investigate the influence of an external force on oscillation whilst not yet having fully understood the phenomenon of free harmonic oscillation.

The problems observed in environments for exploratory learning were ascribed to an inadequate regulation of the student's own learning process (section 1.1). Consequently, the need for support for regulation was postulated. The work presented here aims at the development of means for such support for regulation, more specifically, the planning of the so called 'information space exploration' (see section 1.2). Information space exploration was defined as deciding upon the order in which variables, and relations between variables, need to be explored. In the design for support, the notion of scenario-based organization, as is common in training simulators, has been a source of inspiration.

### 7.1.2 Support for information space exploration

In the authoring environment SMISLE, an enhancement of information space exploration is sought in organizing a simulation environment according to the principles of the Model Progression approach (MPApproach) as originally described by White and Frederiksen (Frederiksen & White, 1988; White & Frederiksen, 1989; White & Frederiksen, 1990). In brief, the MPApproach prescribes the construction of a series of increasingly sophisticated model progression 'levels'[1] rather than the construction of a single target model. Conceptually, these levels are comparable to the scenario's used in training simulators. As with a series of scenarios, the intention of MP is to not initially confront students with the full complexity of a target model but to only gradually introduce aspects essential to an understanding of the target model. Below, we will describe the MPApproach and subsequently review it in the light of the requirements listed in chapter 2.

## 7.2 The original Model Progression approach

### 7.2.1 The approach

Model Progression "seeks to develop in students multiple conceptualizations of a domain" (White & Frederiksen, 1989, p. 93). A motivation to come up with the idea of model progression is the observation that students that have studied physics in a traditional way are frequently found unable to solve simple qualitative problems. "They are observed to have fundamental misconceptions and rely on formulaic solutions" (Frederiksen & White, 1988, p. 250). Especially, a qualitative-quantitative progression should establish the explicit link between a formulaic approach and a more intuitive qualitative one. Generally, the progression approach should support the development of multiple connected conceptualizations.

White and Frederiksen see expertise as "a small set of mental models that embody alternative, but coordinated conceptualizations of system operation" (White & Frederiksen, 1990, p. 100). The authors contend that learning can be seen as an evolution of mental models. With a transition from naiveté to expertise, mental models should become better organized, more coherent, more specific,

[1]White and Frederiksen use the term 'model' to refer to submodels and perspectives that are used in progression. However, for reference to perspectives the term 'model' is confusing. As implemented in the SMISLE, a perspective incorporates a subset of the variables of a model, it is not a self-contained model. To avoid confusion we prefer the term 'level', or MPLevel. An MPLevel can refer both to a submodel and to a perspective upon a submodel

and contain fewer contradictions and misconceptions. Model Progression should provoke such evolution of mental models. "By systematically exposing students to problems that require increasingly sophisticated [mental] models of the domain, students can experience the gradual evolution of scientific models" (Frederiksen & White, 1988, p. 251).

In addition, we would like to stress an under exposed aspect of the approach, namely that of dealing with complexity. A model progression approach allows to split an extensive simulation model into manageable parts by initially hiding much of the complexity of the target model. The progression enables a gradual unfolding of the complexity of the target model to the student. Besides, the careful stepwise introduction of only small units of new content at a time may make each model manageable by itself.

## 7.2.2 Rationales

White and Frederiksen suggest that a learning environment is to be built as a series of MPLevels. These levels should 1) evolve from qualitative zero order, via first order to quantitative models while simultaneously these models and 2) progressively introduce more complexity by adding previously unencountered variables. Yet another type of evolution 3) implements a perspective change. With this latter evolution, students zoom in on the behavior captured in the model. That is, initially they are presented with a high-level functional view, subsequently a behavioral view, and finally with a low level, so called microscopic view.

The here listed dimensions act as 'rationales' for the sequencing of the MPLevels. The rationales will play an important role in this chapter, and will therefore be described more elaborately below.

### 7.2.2.1 Order

Certainly the most important dimension in the work of White and Frederiksen is that of 'order shift'. Although the term suggests otherwise, 'order shift' mainly refers to a progression from qualitative to quantitative models. White and Frederiksen distinguish models that allow reasoning "on the basis of the mere presence or absence of aspects such as resistance, voltage or current" (White & Frederiksen, 1990, p. 106), which they call zero order models. A more sophisticated 'first order' model allows for the study of effects of changes of the aforementioned variables. This first order model is still qualitative. The most sophisticated type of model is a quantitative one. Although the quantitative model may be the most sophisticated, as the authors argue, in human reasoning it is not a substitute for the qualitative models as the various 'order' models are observed to have a function in problem solving processes.

### 7.2.2.2 Elaborateness

A next dimension reflects the so called *degree of elaboration* of a simulation model. According to White and Frederiksen, exploration of a simulation ought to start with focusing on 'gross' or global factors in explaining phenomena. More elaborative models should progressively introduce more complexity by adding variables and previously unencountered relations. The level of elaboration is defined by "the number of qualitative rules used in propagating the effects of changes on the behavior of other components" (White & Frederiksen, 1990, p. 107). This type of model progression can be seen as a simple-to-complex one, as next models "incrementally build on prior models by introducing a new principle or by refining or generalizing previous knowledge" (p. 107).

#### 7.2.2.3 Perspectives

The previously mentioned types of progressions are mainly 'upward', that is, they work toward increasingly sophisticated models. A third type of progression is a lateral one. This progression involves changes in perspective on the phenomenon. Here, MP focuses on alternative means for understanding device behavior. According to White and Frederiksen, when modeling behavior of devices, one might provide functional, behavioral, and reductionistic perspectives on behavior. A functional perspective describes "the purpose [of a system] and how subsystems within the circuit interact to achieve that purpose" (White & Frederiksen, 1990, p. 106). A behavioral perspective presents a macroscopic view at the level of device components. Such a perspective might explain "how changes in the state of one component may cause changes in the state of other components" (p. 106). Finally, phenomena can be presented at a microscopic level, here so called 'reductionistic, physical' models are applied. The three perspectives are presented to the student in the above sketched order, yet they are assumed to be used concurrently in expert problem solving.

### 7.2.3 The MPApproach in the light of the requirements

The MPApproach was claimed to satisfy most of the requirements for support for information space exploration listed in chapter 2.

**Connecting to prior knowledge** The approach anticipates *connection to prior knowledge*, by supporting *iterative cumulation* (see section 3.4.1) by means of a gradual evolution of MP levels. That is, each next level is supposed to only introduce few new elements. By this, each next level builds upon the prior knowledge acquired from the previous levels.

**Tailored rationales** Model Progression reveals a sensitiveness to various learning-related rationales that are specific to the nature of the target domains. The approach, for instance, takes the learner's naive, frequently qualitative, preconception as a starting point. By a qualitative-to-quantitative sequence it attempts to establish a connection from qualitative notions to a quantitative account of behavior. The application of an elaborateness-based rationale also establishes a learning-related sequence. This type of sequence can be seen as simple-to-complex sequence as described in section 4.3.3. Perspective shift is also more a learning-related than a domain-related type of sequence.

**Structure-relatedness** The notion of structure-relatedness was entered as an umbrella for notions of connectivity, consistency of direction and 'natural' direction (see chapter 4). With respect to the first notion, the MPApproach prescribes a form of connectivity between the various MP-Levels. Each next level is supposed to build upon previous levels and as such it is assumed inappropriate to 'jump' to entirely unrelated MPLevels.

With respect to consistency of direction, the model progression approach prescribes norm directions for the three dimensions of progression. This prescription implies consistency of direction. Finally, whether the norm direction is a 'natural' direction can not be answered here.

**Non-directive support** Model Progression is perceived as a potentially powerful method for providing learners with non-directive support. The approach suggests the realization of an environment that provides support at a global level (i.e., between MPLevels) but leaves freedom at a local level (i.e., within an MPLevel). Compared to the exploration space of a complete model, an MPLevel provides a substantially reduced exploration space. This reduction by itself should make exploration more manageable. In addition, with each new MPLevel, only few new elements at a time are introduced. That is, if model progression is designed appropriately, most of the content of a new level is already known, and as shown by Shute and Glaser (1990) amongst others, the more students know about a model, the better they manage to regulate their exploration. Model progression thus aims at reducing the exploration space to the extent that learners are capable of regulation exploration within that space. Within a level, learners are thus supposed to be able to tailor exploration to their own needs while their risk of losing control is substantially reduced. Hence, they are 'helped to do it themselves' (cf., Montessori, 1973), a true form of non-directive support.

### 7.2.4 Toward a model-based authoring tool

Model Progression was assumed to satisfy most of the requirements for support for exploration. It was thus judged to be a likely candidate for support of information space exploration in SMISLE. However, organizing a simulation learning environment according to the prescriptions of the MP approach is not trivial.

White and Frederiksen claim that their model progression approach can "readily be generalized to other domains", if these domains can be modeled in terms of causal structures (White & Frederiksen, 1990, p. 99). However, no firm basis for this claim can be found in their work. Firstly, White and Frederiksen explored the feasibility of the approach within the context of a single domain only. The microworld in QUEST, in which they implemented the MPApproach, was tailored to the domain of electrical circuits. The definition of the dimensions of progression is in several cases specific to this domain. Secondly, although White and Frederiksen describe three dimensions along which multiple levels may progress, they actually implemented and experimented with levels that varied along the 'qualitative-quantitative' and 'elaboration' dimension only. All in all, the prescriptions of the approach are not readily applied to other domains and are sometimes incomplete.

The intention of the exercise described here was to construct an authoring tool that would support authors in imposing MP upon their simulation environments. We thus perceived the need for a more general description of MP. Besides, the requirement that prescriptions should be *non-ambiguous* (section 2.4) was not met. For computer supported instructional design, the original prescriptions were insufficiently precise.

In this chapter, we will describe what was endeavored to make the MPApproach both more general and more precise. To gain insight into the applicability of the method outside the scope of circuit theory, it was decided to analyze a new domain with the question in mind whether this domain could be molded into White and Frederiksen's three dimensional organization. This endeavor, together with a review of related work, lead to a more general description of model progression. A more operational definition was achieved by creating a vocabulary of terms for modeling within the SMISLE and subsequently expressing MP prescriptions in terms of this vocabulary. The actual implementation of authoring support for model progression in SMISLE is described in the following chapter.

## 7.3 Toward generalization

The MPApproach is seen as a potentially powerful measure for support of exploration. This judgment is shared by de Koning et al. (1994) who investigated the applicability of the approach in a fluid dynamics domain of communicating vessels. As our main objective is to develop an instrument for the definition of MP outside the scope of electronic circuits, a crucial issue is if and how the approach could be applied to domains other than just electronics.

### 7.3.1 Method

To investigate if and how the approach could be applied to domains other than electronics, a case study was set up covering the application of the MPApproach in a novel domain: the domain of oscillation. This domain was used in the SMISLE project as an illustration domain from the very beginning. Using the method for domain reconstruction as described in chapter 4 we tried to trace the rationales originally used to sequence this domain. The question to be answered was *whether these rationales had something in common with the above described dimensions of the model progression approach.*

To answer this question, a first step was to trace the rationales behind the sequences found in oscillation material. As in chapter 4, written material covering the subject of oscillation was used as a source of domain expertise. Such material is assumed to provide an overview of the elements considered essential for an understanding of the domain. It thus provides a domain description that is tailored to instruction.

To gain insight into the rationales applied, first the original domain structures were reconstructed from text. In contrast to the analyses of chapter 4 we did not only analyze the texts at the level of the section organization, but also went down to the level of actual text. This level of detail in analysis was necessary to be able to check whether White and Frederiksen's dimensions were applied as rationale anyway. Domain structures were thus reconstructed by searching for elements in text that indicated entities or relations between those entities.

*Entities* were defined as: concepts indicated by a term or a symbol, and frequently accompanied by a definition of that symbol or term. Concepts that were introduced only in illustration material were to be ignored. *Relations* were defined as statements describing the link between two or more entities. For relations, the preciseness of the statement was of interest. To obtain an indication of preciseness, a distinction was made between 1) arithmetical expressions, 2) qualitative expressions indicating a relation plus the direction of this relation, and 3) expressions that only indicated the existence of some relation, where no details were given on the nature of that relation.

Only those elements were extracted from the text that could be considered 'core curricular' elements. Core curricular elements were those elements that reflected the original learning goals. Consequently, case descriptions, being an illustration of an entity or relation that had been mentioned earlier, were ignored. The same held for drawings or graphs that illustrated behavior. If this behavior was described by a relation earlier on, the drawing or graph should be ignored. Drawings illustrating the structure of a device were seen as a description of an entity, a device. Again, if this entity was described earlier on, the drawing should be ignored. Finally, if relations or entities were described more than once, one of the descriptions should be selected as major description, where the remainder should be ignored. For instance, mention of an entity or relation in a summary or advance organizer should be disregarded.

From the entities and relations extracted, the original domain structure was reconstructed. Subsequently, the sequence in which elements were presented was projected onto that domain structure. With this, the source material curriculum could be reconstructed in a 'surveyable' manner. By this, the reconstructed curricula should readily reveal differences and similarities.

### 7.3.2 Source material

Curricula about a topic, such as harmonic oscillation, may vary among books. These variations will be due to personal preferences of the author, but also they might be due to external factors, such as different exam requirements. Thus, to obtain a more general view on the rationales behind sequences in material on harmonic oscillation, we analyzed three frequently used sources covering the same topic. Sources were two Dutch books covering the high school curriculum on physics for 16-17 year old students (Middelink, 1979) and (Nijhof & Koene, 1972) and a physics book from the United Kingdom covering an undergraduate curriculum (Nelkon & Parker, 1970).

**Reliability** To assess the reliability of domain reconstruction, a subset of the material was analyzed in a similar way by a second judge. This subset was a randomly chosen series of pages from each of the three texts, in total a 25%, that is 14 out of 56 pages.

It was found that the fragmentation of text rather than the categorization of those text fragments differed judges. If a similar fragment had been selected, the correspondence between judges with respect to categorization was near to a 100%. Differences occured in the selection of fragments assumed to include core elements. That is, differences in interpretation were observed for the moment of first introduction or 'real' definition of an entity or relation. Yet, with a different selection of fragments, the resulting domain reconstruction could still be the same, that is, similar entities or relations could have been indicated as core curricular elements. Consequently, reliability was calculated in terms of the percentage overlap of the resulting domain representations rather than in terms of similarity of fragmentation or categorization. With this calculation, the percentage overlap of the second judges list of content elements with that of the first judge was 73%.

### 7.3.3 Results

To give an impression of the structure of the oscillation material, we will provide a global overview of the contents and sequence of domain elements found in a representative source, that of Middelink (1979).

Middelink's text on oscillation essentially provides descriptions of example devices that vary in complexity. Simple devices are, for instance, mass-spring systems that may exhibit free harmonic oscillation (Drawing 1 at the left-hand side in Figure 7.1). More complex systems introduce damping (Drawing 2) and/or harmonic forces that act upon an oscillating device (Drawing 3). These devices are used to illustrate the notions of critical damping and resonance respectively. Various accounts of behavior are given, that is, graphs showing displacement or velocity of an oscillating object, force(s) acting upon an oscillating object, or the shift between potential and kinetic energy in oscillating devices.

#### 7.3.3.1 Rationales in oscillation

The question to be answered was whether the rationales found in the oscillation material had something in common with the rationales of the MPApproach. To provide an answer to this question, in the sections below we will describe the current organization, the rationales applied, and review these in the light of the rationales proposed in the MPApproach.

When considering the question of the current organization of the domain, two rationales directly revealed themselves from the material, a multi perspective, and simple-to-complex one. We will start with the most evident organization, the simple-to-complex organization.

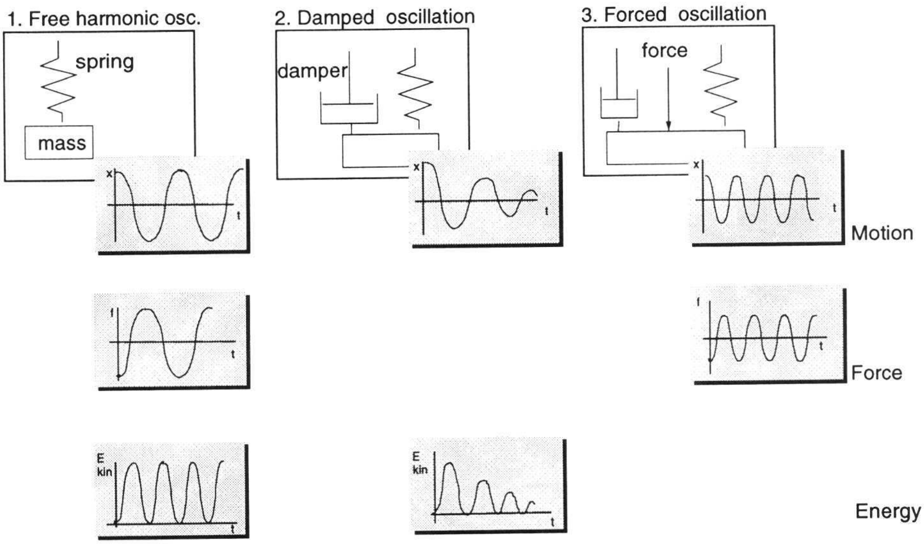



Figure 7.1: Overview of the curriculum structure of Middelink's text on oscillation

### 7.3.3.2 Elaborateness

The oscillation material evidently revealed a simple-to-complex organization based on an empirical complexity rationale. The sources discussed at least two different phenomena, that of free harmonic oscillation and damped oscillation. A third phenomenon, oscillation driven by an external force, naturally resulting in a treatment of the notion of 'resonance', was mentioned in two sources (Middelink, 1979; Nelkon & Parker, 1970). Within the discussion of each phenomenon, especially that of free harmonic oscillation, students were required to investigate aspects such as the displacement and velocity of the point mass of a single type of oscillation before going to the next more complex form of oscillation.

With a progression from free to damped oscillation and from damped to forced oscillation, gradually more complexity is introduced by adding input variables. This gives rise to the observation that a progression from free, damped to externally driven oscillation might very well suit White and Frederiksen's conception of simple-to-complex progression based on the elaborateness dimension.

### 7.3.3.3 Perspectives

A second form of global organization of the oscillation material was a perspective-based organization. The sources were all found to start with a *structural perspective* that smoothly shifted toward a behavioral one. Within this *behavioral perspective*, a **motion view** introduces basic concepts such as amplitude, period, and frequency. This perspective is followed by sections providing diagrams and formulae representing **displacement**, **velocity**, and in two cases **acceleration** as a function of time. Motion is generally followed by a description and illustration of the forces acting upon the oscillating mass, showing how these forces affect displacement. Apparently, this is perceived to be the right moment to show by derivation that the period of the oscillation is independent of its amplitude. Final sections reveal an *energy perspective* that explains how potential energy is transformed into kinetic energy during oscillation. In two texts (Middelink, 1979; Nelkon & Parker, 1970) the effect of damping on the total energy is discussed.

Following this description of the multi perspective organization observed in the oscillation material, a next step was to compare this organization with the perspective organization proposed by White and Frederiksen.

**Functional** The most obvious difference in perspective organization is the complete lack of a functional perspective in the oscillation material. A functional perspective is supposed to reveal at first the purpose of the devices concerned. An electrical circuit is a man made construct, the behavior of which serves a certain purpose, whereas the devices described in the oscillation material are meant to demonstrate a certain behavior, irrespective of the context of application. For the latter type of devices, a functional view on the particular device seems less relevant. Conversely, a view showing a context of application, that is, the real life application of a phenomenon, might be relevant. In the evaluation study in chapter 8, for instance, two high school teachers try to illustrate the phenomena of oscillation by means of real life examples, such as the suspension of a car.

**Behavioral** All three sources were found to visualize and describe behavior of oscillating objects in terms of displacement and velocity. Displacement and velocity together form a motion perspective. In our view, this motion perspective can be similar to the behavioral models of current flow or voltage redistribution as in the circuit domain.

**Microscopic** A reductionistic physical perspective was defined to reflect the behavior of components at a microscopic level. This perspective aims at 'fostering a deeper understanding' of the behavior perspective. In White and Frederiksen's electrical circuits, this meant 'unpacking' the devices and perceiving them at a deeper level of detail. White and Frederiksen, for instance, illustrate the notion of a microscopic perspective by means of a so called dynamic physical model that shows the migration of charged particles over slices of a resistor. This model is assumed to help students to understand the mechanisms behind circuit behavior such as the voltage redistribution.

In classical mechanics, the use of such particle models is less common. Still these particle models might be useful to explain the behavior of components such as dampers or springs and with that to foster a deeper understanding of the behavior of oscillating devices.

**Alternative perspectives** Where no microscopic perspective was observed, the oscillation material revealed two alternative perspectives, namely a force and energy perspective. Force and energy perspectives undoubtedly serve a deeper understanding of the behavior of oscillating devices. A force view may reveal why a mass starts oscillating, the application of the law of conservation of energy may explain why a mass in free harmonic oscillation will oscillate forever. An energy perspective provides an alternative perspective on the notion of damped and externally driven oscillation by showing the dissipation and supply of energy.

Force and energy perspectives were not part of White and Frederiksen's MPApproach. In our opinion, in particular the energy perspective is essential for the explanation of a wide range of phenomena. In the domain of circuit theory an energy perspective may also be essential to a deep understanding of behavior. Curricula on electricity (Middelink, 1980; Nelkon & Parker, 1970; Nijhof

& Koene, 1972) show that an energy perspective, in particular the treatment of Joule's law, is generally found in curricula on circuit theory. Henceforth, an energy perspective was a likely candidate to be a possible perspective in SMISLE's model progression authoring tool.

Finally, White and Frederiksen's notion of 'perspective' is restricted to behavior at different levels of granularity. With that, a highly underexposed aspect of device models in White and Frederiksen's approach is that of the physical structure of devices. In the oscillation material, physical structure of the devices used to illustrate behavior played a role that should not be underestimated.

#### 7.3.3.4 Order

The oscillation material revealed a progression that might partially suit the definition of 'order-based' progression. All three sources described behavior in terms of the following quantities: 'displacement' and 'velocity'. Middelink (1979) and Nijhof (1972) added 'acceleration' of a point mass as a function of time. 'Displacement', 'velocity', and 'acceleration' were described in exactly the given order. As velocity is a derivative of displacement and acceleration is again derived from velocity, the 'degree of derivation' apparently formed a basis for an instructional progression.

In addition, both precise (cf., van Joolingen & de Jong, 1993) and less precise accounts of behavior were found throughout the material. That is, formulae were frequently accompanied by imprecise statements such as "The period of an oscillating mass is independent of the amplitude and is entirely determined by the mass and force constant".

### 7.3.4 Conclusions

In section 7.3 we posed the question whether White and Frederiksen's original dimensional organization could be imposed upon the domain of oscillation. The exercise in the domain of oscillation showed that several of the rationales proposed in the MPApproach are similar to rationales behind sequences by experienced authors. The evident exception is the perspective organization that revealed substantial differences.

It should be noted that the oscillation domain was not too distant from the domain of circuit theory that was used to illustrate the MPApproach. Both the domain of circuit theory and that of oscillation are illustrated by means of systems that are dynamic in nature. The relative straightforward application of a majority of the ideas of the MPApproach gives rise to the statement that it might be worthwhile to continue studying the application of the approach, at least within the context of dynamic systems.

### 7.3.5 Toward generalization

To take this study a step further toward generalization, we reviewed related work describing systems that adopted an approach similar to model progression. The intention of this investigation was to compare model progression rationales with rationales proposed in comparable architectures.

#### 7.3.5.1 Elaborateness

According to White and Frederiksen, exploration of a simulation ought to start with focusing on 'gross' or global factors in explaining phenomena. More 'elaborative' models should progressively introduce more complexity by adding variables and previously unencountered relations (see section 7.2.2.2). In the oscillation study it was concluded that a progression from free, to damped, and finally to externally driven oscillation suited this conception of progression based on an elaborateness rationale.

**Related work** In related work, the notion of simple-to-complex progression is found to be applied frequently. For instance, in the IMTS authoring system (Towne *et al.*, 1989), facilities for the construction of progressively complex views on models are available. IMTS incorporates a mechanism to initially provide students with an incomplete, and by that less detailed, account of behavior. The behavior of this model is 'yoked', that is, filtered from a background model that contains all objects necessary for device operation. This mechanism allows to initially hide detail in the presentation of the behavior of a device. In IMTS, the behavior, however, is not simplified. On the other hand, simple-to-complex progression of behavior may be achieved by using increasingly accurate models, for instance, gradually containing fewer approximations. This type of progression is described in Sime and Leitch (1992) and de Koning et al. (1994).

The previous examples illustrate that models may vary in complexity due to differences other than the number of relations used to generate behavior only (see section 7.2.2.2). Some configurations of components may be inherently more difficult than others, for example, serial circuits of composed of resistors are generally perceived easier than parallel ones. Some device components may in itself be easier to understand than others (cf., de Koning *et al.*, 1994). Regarding all possible grounds for differences in complexity, we advocate a broader conception of the simple-to-complex dimension. As will be discussed in section 7.5.1.1, we have attempted to list aspects that together determine the complexity of a model. To indicate this broader approach, we have traded the term 'elaborateness-based' progression for *simple-to-complex* progression.

### 7.3.5.2 Perspectives

Perspective shift was defined to be a lateral progression. Rather than providing more and more sophisticated views on behavior, it focuses on alternative views for understanding device behavior. According to White and Frederiksen, when modeling behavior of devices, one might provide functional, behavioral, and microscopic perspectives on behavior. In the oscillation material, a perspective dimension was found to act as a rationale. However, the actual nature of the dimension was different from that specified by White and Frederiksen. In the oscillation material the following perspectives on behavior were given: motion, force, and energy. In contrast, no functional and microscopic perspectives were found.

White and Frederiksen's notion of 'perspective' is restricted to behavior at different levels of granularity. Structural models were never presented as an alternative conception of a system, yet in our opinion, also in QUEST they do form an important vehicle to convey ideas about the domain. In QUEST, learners are provided with circuit components which allow them to create new circuits that enables them to experiment with different configurations. Such experiments may help them understand the consequences of different topologies as serial or parallel circuits. Since knowledge of the topology of devices plays an important role in diagnosis, for example, the structural view should have received more attention in the MPApproach.

**Related work** With Moyse (1989) and Spiro et al. (1991) we believe that the notion of alternative perspectives on a phenomenon is valuable from an instructional point of view. First, effective problem solving frequently demands a multiple perspective approach. Moyse, for instance, argues that a single perspective, or 'problem space', is usually not sufficient when it gets to the harder problems.

He illustrates this stance with a diagnostic problem that requires analysis from at least an electrical and a mechanical perspective. In the field of diagnosis, many stress the use of multiple connected models. For example, Abu-Hanna (1994) suggests the use of separate but connected models of structure, function, and behavior to allow for flexibility in diagnosis. Where a target task demands for a multiple perspective approach, the learning material should reveal this organization.

The results of the study on oscillation and the previous example suggest that the original definition of perspectives might have been too narrow, but they also illustrate that a multiple perspective approach may be worthwhile, sometimes even essential to convey the complexity of a domain. We would, however, prefer to use a broader conception of perspectives and, for instance, include a structural model of a device as a potentially relevant perspective.

#### 7.3.5.3 Order

The 'order' dimension in the work of White and Frederiksen has given rise to a substantial amount of confusion. Though the dimension is labeled 'order', it was assumed to include progressions along two separate dimensions. Concurrently, the order[2] of the models might increase and the nature of the models shift from qualitative to quantitative, or as we defined it before, get increasingly precise. The oscillation material was indeed found to reveal a progression that could be seen as order, or *derivation-based* as well as one that was precision-based (see section 7.3.3.4).

**Related work** In our view, progressions along these two dimensions may both be useful and do not necessarily have to be combined. This is, for instance, illustrated by Plötzner and Spada (1992) who implemented a progression along a qualitative-quantitative dimension only in the multiple model architecture of their system DiBi. In addition, Plötzner and Spada, and van Joolingen (1994) showed that a further distinction with respect to different levels of 'precision' (van Joolingen & de Jong, 1993) of qualitative accounts of behavior serve an instructional need. We, therefore, have adopted the notion of levels of *precision* to refer to a dimension that starts with imprecise statements, such as, $y$ is related to $x$, and ends with quantitative statements, such as $y = 4.5 \times x$. Besides, we will refer to 'order' in its traditional sense, that of degree of mathematical derivation. To avoid confusion, we have labeled this dimension *derivation-based* rather than 'order-based'.

### 7.3.6 Additional explorations

A next step would be to get to a more operational definition of the approach. This would allow application of a similar interpretation of the MPApproach to various domains. However, before this can be done, two additional issues needed to be resolved, that of combining rationales and that of the nature of progressions.

#### 7.3.6.1 The dimension space

An additional comment that could be made on the original MPApproach is that no clear statements are made on how progressions along different dimensions might be combined. In chapter 2 it was contended that a prescriptive model should include statements on how to combine various rationales. Statements on combining can, for instance, refer to a categorical dominance of particular rationales for coarse- respectively fine-grained organization. Reigeluth and Stein, for

[2] The term 'order' is used here in its common meaning in the field of physics, that of degree of mathematical derivation

instance, prescribed the application of combination of a hierarchical- and a prerequisite-first rationale. For a coarse-grained organization the hierarchical rationale took categorical dominance over the prerequisite-first rationale. In general, if more than one rationale is to be applied, it should be made explicit what rationale should be used for what level of organization.

In the work of White and Frederiksen, MPLevels were said to vary along different dimensions. However, no statements were made on categorical dominance, nor on different levels of granularity in the organization of material. The oscillation study made clear that different dimensions might play a role at different levels of granularity. In the oscillation domain, progression along a simple-to-complex dimension resulted in a coarse-grained decomposition into three large clusters. In contrast, 'precision' progressions were found at a finer grained level only, that of single relations. The following figures illustrate the relation between the four main rationales identified in this study. Figure 7.2 shows an abstraction of the overall organization of the material as present in a representative source (Middelink, 1979). This coarse-grained organization is projected onto *simple-to-complex* and *perspective shift* dimensions. The perspectives that were covered by Middelink are indicated gray in the figure. Obviously, not all potential perspectives were equally useful for instruction as, for instance, some might have been perceived too difficult for the target population.

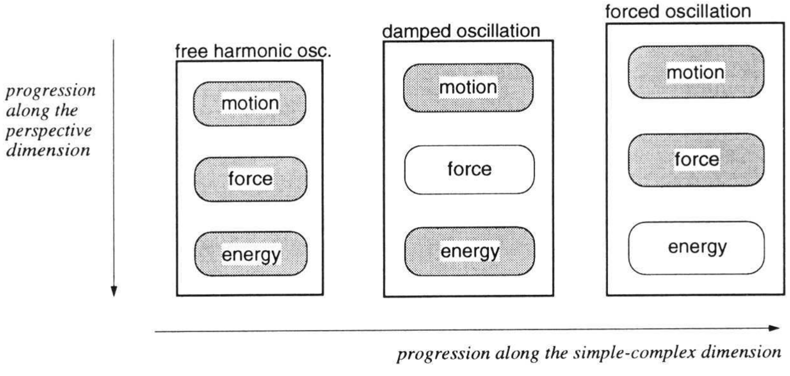



Figure 7.2: A perspective/simple-to-complex dimension space (as present in (Middelink, 1979))

A second figure (Figure 7.3) depicts a finer grained level of organization. Here, one of the perspectives is opened up and at this level *derivation-based* and *precision* progressions were observed. Derivation-based progression was only found within the motion perspective, whereas precision progressions could be found throughout the material.

A remark must be made concerning the level at which the precision progressions were found. None of the books provided a qualitative account of behavior of a full model before going to a quantitative level, though this might have well been possible. Apparently, the authors perceived it important to connect the qualitative and quantitative level, that is, to accompany formulae by a qualitative description. In written material such an organization is common, in simulations, a precision rationale is more likely to act at a more coarse-grained level of organization.

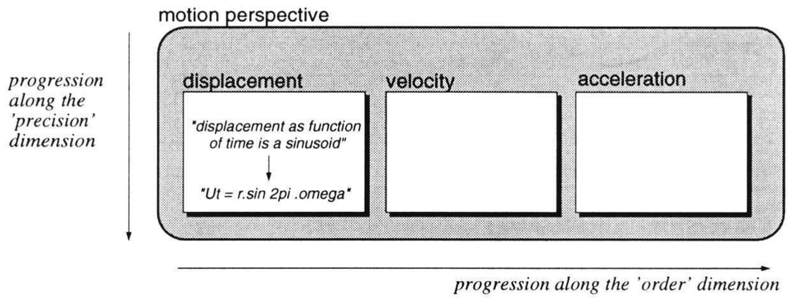



Figure 7.3: A derivation-based/precision dimension space (as present in (Middelink, 1979))

#### 7.3.6.2 Progressions

A final question to be answered was whether the directions of sequences in the oscillation material were in line with those prescribed in the work of White and Frederiksen. In the oscillation material, perspectives, different from those in White and Frederiksen, were consistently described in the order 'motion-force-energy'. As expected, models at different points on the simple-to-complex dimension were found to progress from simple to complex. Finally, relations differing with respect to degree of derivation were described from lower order to higher order ones. Thus, simple-to-complex and derivation-based progressions were similar to the ones proposed in the MP approach.

Surprisingly, the oscillation material showed examples of progression from qualitative descriptions to quantitative ones as well as reverse direction progressions. Frequently, sections started with the derivation of the formulae describing a certain behavior while only later the behavior was described in more qualitative terms.

A final observation on progression addresses the issue of connecting to prior knowledge. All sources were found to provide in an early stage a link to the uniform circular motion. Harmonic oscillation was introduced by means of a one-dimensional projection of circular motion. Formulae for displacement, velocity and acceleration were subsequently derived from formulae describing circular motion. With this reference to uniform circular motion a connection to prior knowledge was established, since in all cases circular motion had been treated in preceding chapters. Given an understanding of the phenomenon of circular motion, it is only a small step to an understanding of the phenomenon of oscillation. Apparently, the necessity of connection to prior knowledge and that of limiting the amount of new material to be introduced, was recognized by all authors.

With this we have arrived at the end of this section on generalization. A next exercise will be on operationalization.

## 7.4 Toward operationalization

A first step toward operationalization is an attempt to define MP in terms of generic aspects of domains. In the context of the SMISLE project (see section 1.4), domains are those models that can be expressed in terms of the formalisms provided by the SMISLE authoring environment.

In the following sections, an attempt is made to express MP in terms of primitives of the modeling formalisms used in SMISLE. To this end, we shall briefly describe SMISLE's modeling formalisms and subsequently provide a vocabulary by which generic aspects of models can be described.

Finally, an attempt shall be made to provide an 'operational' prescriptive model for MP (MPModel hereafter). This model shall be used as a basis for automized generation of MPLevels as implemented in an authoring system, named MPTool (described in chapter 8).

### 7.4.1 SMISLE's modeling formalisms

**SMISLE's modeling tool** In SMISLE, models are not created from scratch. The SMISLE modeling tool (Scott, 1993b; Scott, 1993a) basically provides building blocks at three different levels (see figure 7.4). The most primitive blocks represent extended Petri net elements (see e.g., de Jong *et al.*, 1994).

These primitive blocks are capable of executing simple mathematical operations. Besides, the blocks can be aggregated to form compound blocks, these compound blocks can be reused and form the second level of building blocks. This is the 'functional block' level. Some compound blocks have a special purpose, they form the building blocks for bond graph modeling (see Karnopp *et al.*, 1990; Amsterdam, 1993). Bond graphs form the highest level formalism and it is this level at which MPModel will act.

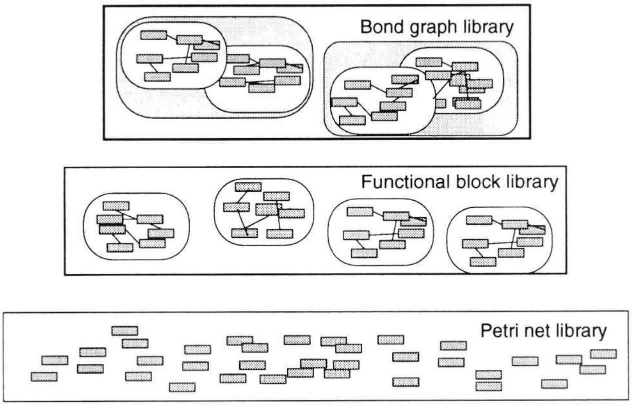



Figure 7.4: The structure of the modeling tool library

**Bond graph modeling** The bond graph formalism is tailored to modeling dynamic systems, that is, those systems whose behavior as a function of time is important (Karnopp *et al.*, 1990). Bond graphs are used, in particular, to model devices or phenomena in the fields of mechanics, electronics, thermodynamics, and hydraulics (see e.g., Top, 1993; Amsterdam, 1993). The formalism does provide the author with high level building blocks that model behavior in terms of a small set of ideal elements. Some of these elements correspond to ideal physical elements, such as masses and springs. Other elements do not always correspond to separate physical elements, but model, for instance, resistance and inductance effects.

Each bond graph element has instantiations in the above mentioned fields. For example, the bond graph element *'capacitor'* models the behavior of a *spring* in mechanics, in electronics that of a *condenser* and in hydraulics that of a so called *hydraulic accumulator*.

In bond graph models, behavior is always modeled in terms of *flow, effort* and *energy flow* and their derivatives. Effort, flow and, energy have different instantiations in different domain types. For instance, the notion of *'flow'* refers to *velocity* (mechanics), *current* (electronics) or *volume flow* (hydraulics). In consequence, the behavior of, for instance, an oscillating device would be modeled in terms of velocity (flow), force (effort) and energy transformation (energy flow), that is, the transformation of potential into kinetic energy.

In SMISLE, models are configured by selecting elements from the library of bond graph elements and subsequently linking these to construct a directed graph. Only if (parts of) a system cannot be modeled in terms of bond graphs, SMISLE authors will need to step down to the functional block or even to the Petri net level.

### 7.4.2 Model progression imposed upon SMISLE models

The question raised was how MP could be expressed in terms of generic elements of SMISLE models. Thus, before going into any further detail on the modeling formalisms, we shall illustrate 1) how the phenomenon of oscillation could be modeled using SMISLE's formalisms and 2) how MP can be expressed in terms of the modeling formalisms.

**Oscillation and bond graph modeling** Oscillation is typically one of the phenomena that are suitable for modeling at the bond graph level. The most primitive device exhibiting free harmonic oscillation can be modeled by just connecting an inertia (a mass) to a capacitor (a spring).

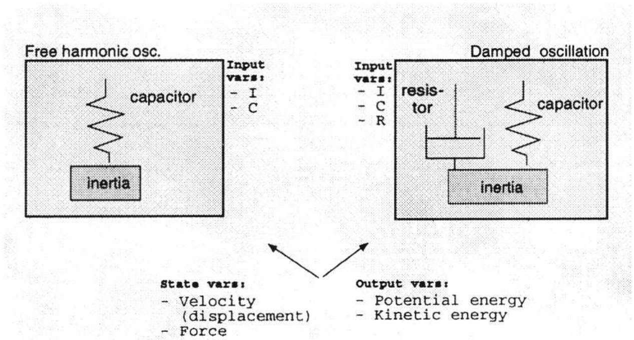



Figure 7.5: Models of devices exhibiting free harmonic (left) and damped oscillation (right)

Such an ideal mass-spring system is depicted on the left-hand side of Figure 7.5. The right-hand side diagram[3] in the same figure depicts the more complex model of a mass-spring system with friction. This system exhibits damped harmonic oscillation. Friction is modeled here by means of a 'resistor', in the field of mechanics known as a 'damper' or 'dash pot'.

Each of the bond graph elements has a parameter, or in SMISLE terms, an 'input variable'. For the mass element this is the inertia parameter $I$, for the spring it is the capacitor parameter $C$ and for the resistor it is the resistance parameter $R$ (see also Figure 7.5).

[3]Both diagrams are derived, with permission, from the SETCOM system. The SETCOM was built by van Joolingen and described in (van Joolingen *et al.*, 1995)

In bond graph models, behavior is modeled in terms of the state variables *flow* and *effort* and output variables indicating *energyflow* (and their derivatives). Modeling a mass-spring system thus implies that behavior is modeled in terms of displacement and velocity (*flow*), force (*effort*) and energy transformation (*energy flow*), that is, the transformation of potential into kinetic energy.

**Model progression** Then, how does model progression relate to the aforementioned aspects of a bond graph model?

**The simple-to-complex dimension** With respect to the simple-to-complex dimension, an evident difference between the model of simple harmonic oscillation (SHO) and that of damped oscillation (DO) (still Figure 7.5) is the number of bond graph elements the models are built from. The simpler model (SHO) is built using less elements than the complex one (DO), consequently the simple model has less input variables than the model of DO. The number of input variables determines the degrees of freedom of a model. Degrees of freedom of a model might be an indication of complexity.

Moreover, with adding bond graph elements, the behavior captured in a model changes substantially. The displacement of the oscillating mass in a simple mass-spring system can be characterized by a sine curve. After adding a resistor component to the mass-spring system, behavior is characterized by a sine curve that 'fades out'. The behavior of a forced oscillator would again be more complex. A forced oscillator system exhibits different types of behavior; a sine curve when oscillating at the eigenfrequency, a fading sine curve if resistance is larger than the driving force, or a sine curve with increasing amplitude.

With adding bond graph elements to a model, the degrees of freedom of a model increases and the behavior captured in the model changes. In the example of oscillation, the behavior could be perceived to increase in complexity. Therefore, for the illustration domain, the number of bond graph elements in a model was an indicator for complexity.

**The perspective dimension** With respect to perspectives, in section 7.3.4 we claimed that the 'motion', 'force', and 'energy transformation' were valid perspectives in the domain of oscillation. The flow variable 'velocity' represents a motion perspective, the effort variable 'force' represent a force perspective and the energy flow variables, showing the transformation between potential and kinetic energy, represent an energy perspective. Evidently, the desired perspectives can directly be derived from generic variables. We, therefore, claim that in the oscillation example the generic effort, flow, and energy flow variables each represented a distinct perspective.

**The derivation-based dimension** The dimension 'derivation-based' was previously defined to reflect degree of mathematical derivation. The oscillation material revealed a progression on the derivation-based dimension (section 7.3.3.4). Within the motion perspective behavior was described in terms of 'displacement', 'velocity', and 'acceleration' of a point mass as function of time. In SMISLE's implementation of the bond graph formalism, the integral of the flow variable, 'displacement', is always provided. In consequence, at least within the flow perspective two separate derivation-based views are possible.

**The precision dimension** The bond graph formalism does not support modeling at different levels of precision, neither does the functional block nor Petri net formalism. Thus, progression along this dimension is not possible within the context of the current SMISLE formalisms.

### 7.4.3 Toward a generalization

For the oscillation example, three types of progression, as presumed valid in the oscillation domain, could be expressed in terms of generic aspects of bond graph models. Complexity was expressed in terms of the number of bond graph elements in a model. Perspectives could be expressed in terms of accounts of behavior in terms of flow, effort, or energy variables. Finally, derivation-based views could be expressed in terms of the flow and effort variables and their integrals.

A crucial issue is whether the prior statements concerning the simple-to-complex, the perspective, and derivation-based dimensions are valid for all SMISLE bond graph models. To answer this question, we shall from now on adopt a top-down approach. We will outline generic aspects of SMISLE models, resulting in a vocabulary for reasoning about these models. For an MPApproach to be operational, simple-to-complex progression, perspective, and derivation-based view shift need to be expressed in terms of this vocabulary.

### 7.4.4 A SMISLE modeling vocabulary

To map generic aspects of SMISLE models we have used Abu Hanna's framework (Abu-Hanna, 1994) for modeling devices. Among alternatives, Abu-Hanna's framework was considered most appropriate since it separates *ontology*, the vocabulary that is used to describe a device, and *theory constructs*, the constructs used to make statements about the device. Our interest was not so much to model devices, but to create an ontology that would allow us to express MP in terms of generic aspects of SMISLE models. As such, we needed different theory constructs but could still reuse many ideas on device ontology as put forward by Abu-Hanna.

A second reason to adopt the framework was its multi-layered organization. We perceived it useful to make an explicit distinction between statements on MP that held 1) for all SMISLE models, 2) for bond graph models only, 3) for bond graph models constructed from specified elements only, or finally 4) for models that were restricted to a single domain type only.

In the following section we shall apply Abu-Hanna's framework to describe the vocabulary for SMISLE models. Figure 7.6 provides an overview of the various layers. In this figure, the layers indicate the distinct levels of generality, where the top layer is the most general one. Graphics such as boxes and ellipses contain ontological constructs. Lines between ontological constructs indicate specialization relations.

With respect to the contents of the vocabulary, it must be noted that we had a representational/ontological commitment (Wielinga & Schreiber, 1993) to refer to the primitives of the bond graph and petri net formalisms. For example, we would rather use the term *n-port* than 'component' since the first is a primitive of the bond graph language.

A second commitment of 'efficiency' had to do with abstractions that had already been made in the SMISLE system. For instance, variables had been categorized in terms of input, state, and output variables. These terms were nonexistent in the modeling formalisms but had been introduced in the SMISLE to support interfacing to the graphical interface and to the assignments, explanations and hypotheses scratchpads. In the vocabulary, we would rather use currently available abstractions than come up with new ones.

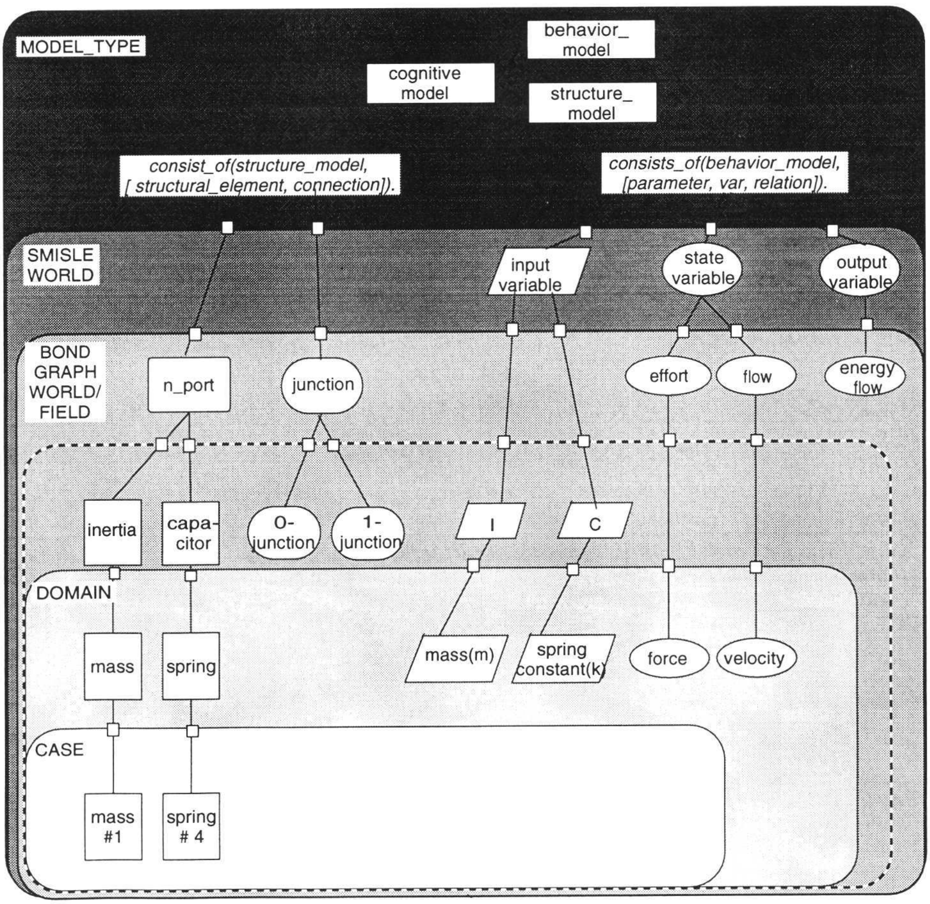



Figure 7.6: The SMISLE modeling vocabulary, using Abu-Hanna's framework for domain modeling

**The vocabulary** In the top layer, the **model type** layer, it is described which epistemological types of models can be constructed, given the scope of the modeling formalisms. In SMISLE, models of structure and behavior are anticipated. Following Abu-Hanna, models of structure are generally composed of structural elements, ports, and connections. Models of behavior are composed of parameters, variables, and relations. Not all composing elements have explicit counterparts in the SMISLE system. The so called SMISLE **world** layer contains just the vocabulary that applies to all SMISLE models and as can be found here, SMISLE knows generic notions for parameters and variables only, that is, all conceptual models have *input-*, *state-*, and *output variables*, irrespective of the formalism used. These are the only constructs that are generic to all SMISLE models, no general constructs for structural elements are available.

The implication of such a limited vocabulary at the SMISLE world level is that little can be said about SMISLE models in general. If, for instance, we aim at expressing the model progression dimension 'complexity' in terms of the number of structural elements of a model, the SMISLE vocabulary fails to support this. Thus, this expression on complexity could not be realized, provided the current vocabulary at the SMISLE world level.

Little can be said in general about models composed of functional or Petri net blocks. While the expressive power of both formalisms is extensive, the formalisms lack high level predefined constructs. The bond graph formalism, however, does provide high-level constructs that might be useful in a model progression theory. Therefore, we shall from now on focus on constructs provided by the bond graph formalism. With this we have arrived at the third level, the **bond graph world/field** level. Here the structural element has a counterpart, being a bond graph element, named *n-port*. In addition, the state and output variables have been further specialized. *Effort* and *flow* variables are state variables, whereas *kinetic-* and *potential energy* are output variables.

The **bond graph field** layer describes the actual bond graph elements. Here, we have displayed only two examples, the *inertia* and *capacitor* one-ports. The **domain** layer provides a connection between bond graph elements and the actual ideal element in different domains such as mechanics, electronics etc. It should be noted that none of the constructs of the domain layer are explicitly represented in the SMISLE. In the DISCOURSE system (described in Tait, 1994) it can be observed that the presence of domain level constructs allows for a more intuitive way of modeling where more common constructs such as *mass* and *spring* are used instead of abstract notions such as inertia and capacitor. Hence, we see the lack of a domain layer as a (temporal) omission in SMISLE and have therefore added domain level constructs to the vocabulary. Finally, the **case** layer defines elements of models that directly correspond to a concrete system, in this example the previously illustrated mass-spring device.

## 7.5 MPModel

The above specified vocabulary provides primitives to describe model progression in terms of generic aspects of SMISLE models. The declaration of the vocabulary that is used to make statements on model progression can be found in Appendix B. To describe the MP dimensions, we aimed at the highest level of generality to make statements that apply to a broad range of SMISLE models. Only if MPLevels could not be described in terms of high-level constructs one would have to descend to lower levels.

### 7.5.1 The dimensions

#### 7.5.1.1 The simple-to-complex dimension

**The total number of variables** At the SMISLE world level, complexity can only be expressed in terms of the *input, state* and *output* variables of models. The number of variables in a model might give an indication of the (empirical) complexity of the model. However, it is a very weak indicator as we have no knowledge of the underlying behavior of a model. By lack of additional evidence, such a weak heuristic on complexity is not yet accepted to be part of MPModel.

**The number of n-ports** Information on the complexity of behavior of a model can be derived when descending to the bond graph world level. With each new n-port 1) one or more *input variables* are added to the model and thus the degree of freedom increases, and 2) the model of behavior of a system gets more extensive in terms of the number of relations it is composed of. The empirical complexity (see section 4.3.1) thus increases, whether the behavior generally becomes more difficult to understand should be investigated. The simplex-to-complex progression is thus based on an empirical complexity rationale rather than on a 'learning-related difficulty' rationale.

Due to the first factor, increase in degree of freedom, we have decided to accept the number of n-ports, and with that the number of input variables, as an indicator for complexity. Hence, if the n-port $A$ is composed of a non-empty subset of the set of n-ports of model $B$, model $B$ is assumed to be the most complex model of the two (see Appendix B). In the evaluation of MPModel in chapter 8 it should indeed be investigated whether this operationalization generally leads to a series of increasingly difficult models.

**The inherent difficulty of n-ports** One the shortcomings of the original MP approach was that it did not consider differences in the inherent learning-related difficulty of the model components (cf., de Koning *et al.*, 1994). Therefore, by descending the framework to the level of specific n-ports, that is *inertia, capacitor* etc., a refinement of the former heuristic might be made by taking into account the relative difficulty of the n-ports. We firmly believe that there are differences in learning-related difficulty among the n-ports. In written instructional material (Middelink, 1980; Nelkon & Parker, 1970; Nijhof & Koene, 1972) on circuit theory, it could be found that, for instance, resistors are generally treated before capacitors, which are again treated before transformers. In our view, the order of treatment suggests here increasing relative difficulty.

In this work no in-depth study has been made on the relative difficulty of bond graph elements. Therefore, we can only indicate that further study is needed to get to a useful estimate of the relative difficulty of each n-port. As the set of n-ports is very limited we believe that such a notion of relative difficulty for each library element is achievable.

**Parallel versus serial connections** When models are constructed of identical sets of n-ports, a refinement to the notion of difficulty can be made by considering the configuration of the n-ports. When regarding the domain of elementary circuit theory, it can be found that parallel circuits composed of resistors are generally perceived more difficult than serial ones. It should be studied whether such differences in difficulty based on the configurations of n-ports is also true for models composed of other types of n-ports.

#### 7.5.1.2 Perspectives

Referring back to the written material on oscillation, a clear view on perspectives within the oscillation domain emerged. For oscillation apparently valid perspectives are; motion (displacement and velocity), force and energy. Motion, force and energy transformations are in bond graph terminology: *flow, effort, and energy flow*. These variables form the core of models of behavior.

The SMISLE provides facilities to inspect all three variables separately as a function of time. In consequence, it is possible to regard these three variables as default perspectives. Whether this choice of default perspectives is valid from an instructional point of view, is an other issue. We have studied just one example domain and in this case the flow, effort and energy perspective make a perfect match with perspectives chosen by three experienced teachers. Obviously, one example does not provide a sufficient basis for a claim on instructional validity of the effort, flow and energy perspective. However, their instantiations in the other three domains (electronics, hydrodynamics, and thermodynamics) certainly refer to core concepts in the high school curriculum. In the domain of electrical circuits, for instance, default perspectives would be current, voltage and electrical energy of a modeled circuit.

In Appendix B a definition of perspectives in terms of the SMISLE vocabulary can be found.

#### 7.5.1.3 Derivation-based views

In bond graph modeling there is frequent mention of the variable 'displacement' of which flow is a derivative. Separating views on displacement and flow might be appropriate from an instructional point of view, as was reflected in the oscillation material study where displacement, velocity and also acceleration were treated separately. Momentum, the integral of effort, is mentioned far less frequently and seems to represent a less conventional viewpoint (see also Karnopp *et al.*, 1990, p. 19). Notwithstanding that, degree of derivation is evidently a rationale that is applied to sequence the subject matter for the student. Therefore, the following derivation-based views will be defined upon the effort and flow perspective: momentum and effort for the effort perspective, and displacement and flow for the flow perspective. Note that for relatively limited models this level of granularity might be too low.

In Appendix B a definition of derivation-based views in terms of the SMISLE vocabulary can be found.

#### 7.5.1.4 Precision

The bond graph formalism does not support modeling at different levels of precision, neither does the functional block nor petri net formalism. Therefore, the precision dimension had to be excluded from the SMISLE specific MPModel.

### 7.5.2 The dimension space

Having operationalized some of the dimensions along which model progression can be defined, we can now describe MPLevels in terms of those dimensions. With derivation-based views defined to be sub perspectives, only two dimensions remain, a perspective and a simple-to-complex dimension. An MPLevel is then characterized by a point in a two-dimensional space (see Figure 7.7).

No clear indication for categorical dominance for either of the two dimensions was observed. Hence, for the combination simple-to-complex progression and perspective shift two major options exist. First, the simple-to-complex progression can be used for a coarse-grained organization, while MPLevels for perspectives are specified within those simple-to-complex levels. Second, perspective shift can also be the basis for the coarse-grained organization. In that case, a progression of simple-to-complex levels could be provided within a single perspective. With each perspective shift, again the same series of simple-to-complex models can be presented. We have no reason to believe that either one of these organizations is less valid, and both organizations will thus be allowed.

### 7.5.3 Progression

A final aspect of an operational model progression theory is a set of rules that specify the direction in which model progression levels are to be presented to the student.

- **Simple-to-complex progressions** In line with the vast majority of theories on sequencing, it is suggested to start with levels for simple models and progress to the more complex ones.

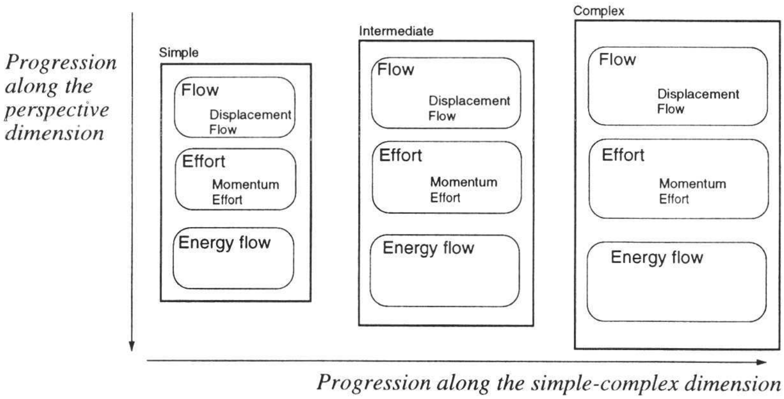



Figure 7.7: The resulting two dimensional MP space

- **Perspective** For perspectives, the order of presentation is less evident. Differences in level of abstraction play a role. The effort and energy flow perspectives refer to abstract notions that explain the flow perspective. Flow variables most directly relate to observable phenomena, thus to concrete experience. Connection to prior experience is an essential starting point (Ausubel, 1963). We, therefore, suggest to start at the flow perspective and only afterwards provide the effort and energy perspective. It was in this way that perspectives were presented in the oscillation material.

- **Derivation-based** For derivation-based progression a similar argument can be made, lower order models are supposed to model concrete phenomena, phenomena that directly relate to human experience. Higher order models are derived and thus more abstract, more remote from experience. This leads us to the suggestion that lower order views should be presented before higher order ones. For displacement and its derivative -flow-, such a sequence was found in the oscillation material. Momentum was, however, not present as a perspective in the oscillation material.

## 7.6 Summary

This chapter was dedicated to tailoring the Model Progression approach, to make it both more generally applicable and more operational. The intention of this exercise was to create a prescriptive model (MPModel) for use in a model-based authoring tool (MPTool).

A first step toward generalization was to investigate whether the dimensions originally described by White and Frederiksen could act as rationales for the organization of domains other than the domain of circuit theory in which terms the model progression approach was described. From a study in the application of the MPApproach to a novel domain, we could conclude that for the domain of oscillation all previously mentioned dimensions were found to act as rationale. The exact nature of the dimensions, however, frequently differed from the descriptions as provided by White and Frederiksen.

From an analysis of related work in the field, we refined the original three dimensional model progression approach to a four dimensional one. The resulting dimensions were:

- simple-complex
- perspective
- derivation-based view
- precision

A step toward operationalization was an attempt to define MP in terms of generic aspects of SMISLE models. In the following chapter a description will be provided of the implementation of the resulting MPModel in an authoring tool for model progression. In a subsequent evaluation of the authoring environment, the validity of MPModel was subject to investigation.

# MPTool: a Model Progression authoring Tool, design and evaluation

# 8

## 8.1 Introduction

In chapter 7 an attempt was made to generalize and subsequently to operationalize the model progression approach by describing elements from the approach in terms of generic aspects of SMISLE models. The so resulting MPModel should be the foundation for a model-based authoring tool.

The work described here was done in the context of the project SMISLE (see section 1.4). The intention of this project was to provide authors with support for the construction of simulation-based learning environments and integrated forms of instructional support, the so called measures (see de Jong *et al.*, 1994). Model progression is one of those measures. Model progression in SMISLE implies providing a series of model progression levels (MPLevels) that both gradually progress in *complexity* and provide various *perspectives* on the simulated phenomena.

An authoring tool for model progression should provide technical and conceptual support. The tool should not only allow authors to impose a series of MPLevels upon SMISLE models, it should also support decisions upon the nature and scope of such a series of MPLevels. As such, the instructional design of model progression is to be supported as well.

The question raised in this chapter is how to provide such technical and conceptual support. This chapter describes 1) a first prototype of an authoring tool for the design and implementation of model progression, 2) an evaluation study to assess the adequacy of the current implementations of the tool and to assess the validity and efficacy of the conceptual support. The evaluation study was highly exploratory in nature and served to generate several ideas for improvement of support, hence, a final element of this chapter is 3) a proposal for revision of the tool.

## 8.2 Model progression in SMISLE

This section starts with a description of a prototype of the authoring tools. To be able to sketch the working of the tools, we will first explain the architecture of a Multimedia Integrated Simulation Learning Environment (MISLE) that is created by means of the SMISLE.

### 8.2.1 Model progression from the author's perspective

Model progression has a pivotal role in a MISLE. To illustrate this, we have sketched the architecture of a learning environment (see Figure 8.1). The core of a MISLE is formed by one or more simulation models, represented by the dark grey box at the left hand side in the figure. A simulation model is composed of variables and relations. In the MISLE an MPLevel allows to select a simulation model. In addition, an MPLevel can act as a 'filter' upon the variables to be manipulated and investigated by the learner. Model progression can then be realized by providing a series of models, a series of filters upon one and the same model, or by combinations of both.

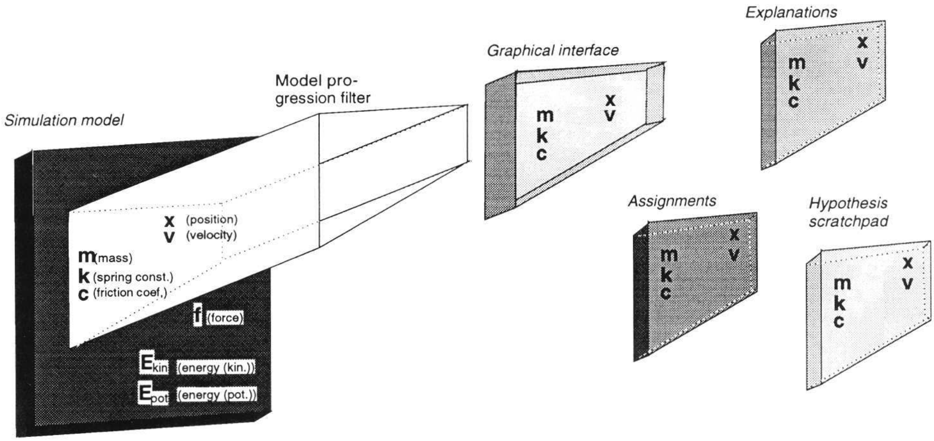



Figure 8.1: The MISLE architecture

The effect of setting a filter on the variables of a simulation model propagates through the MISLE. It filters the variables present in the graphical interface, in the assignments, explanations, and hypothesis scratchpads.[1]

In the example as illustrated in Figure 8.1, within an MPLevel for a motion perspective, only the motion variables ($x$-position and $v$-velocity) are present for investigation. Thus, although force and energy variables are present in the underlying simulation model, they are not shown in the graphical interface, neither in the hypothesis scratchpad or assignments, nor can explanations be dedicated to those variables. In consequence, the learning environment is tailored fully to the MPLevel it is connected to.

A second aspect of an MPLevel is that it enables to set a simulation in a particular state. This is done by setting initial values for the variables and imposing constraints upon the range of values a variable may assume. The setting of an initial state is essential to be able to create relevant situations for learning. For instance, to have a pilot trainee experience bad weather conditions in a flight simulator, the variables for weather conditions are to be set to extreme values. Also, in the evaluation study (section 8.4), authors were observed to create several states within a single variable filter. Within a level for damped oscillation (DO), by setting the friction coefficient at different initial values, MPLevels were created for critical damping, sub- and super-critical damping respectively (see section 8.4.3). In this example, a coarse-grained organization was designed by means of a series of variable filters for simple harmonic oscillation (SHO), damped oscillation (DO), and forced oscillation with damping (FDO) respectively. Within DO a refinement was made by defining specific initial states for critical damping, sub, and super critical damping. As this example illustrates, the state settings can be used to create a finer grained organization than would be possible by using variable filters only.

The tools described in this chapter only support the creation of variable filters. The creation of state settings is supported by a different part of the SMISLE.

[1] For a description of measures for support in SMISLE, the reader is referred to (de Jong *et al.*, 1994; de Jong & van Joolingen, 1995). Van Joolingen et al. (1995) provide illustrations of those measures for three different domains.

### 8.2.2 Model progression from the learner's perspective

A series of MPLevels, in a specified order, constitute model progression. With each next MPLevel, the learning environment evolves. To illustrate this evolution, below two interfaces are shown as are present in a MISLE on oscillatory motion named SETCOM (SETCOM was built by van Joolingen and described in (van Joolingen *et al.*, 1995)).

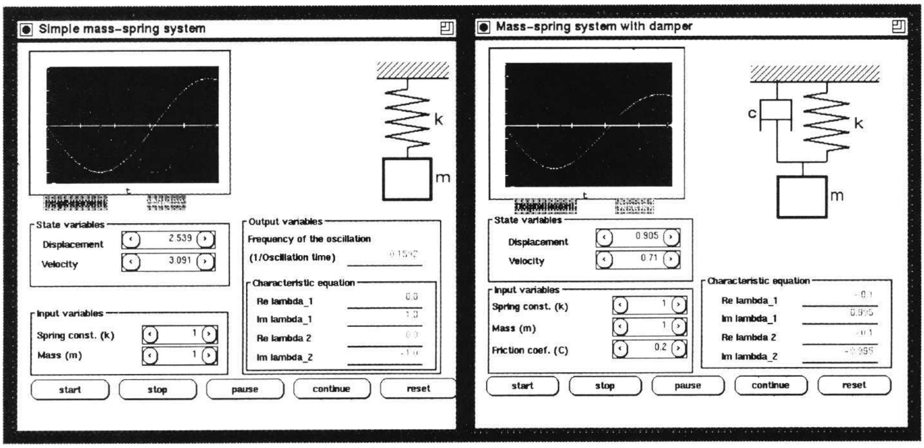



Figure 8.2: Two examples of interfaces with different variable filters (adopted with permission from van Joolingen)

In the SETCOM, the author decided to provide learners with a motion perspective on a series of MPLevels that vary along the simple-complex dimension. The learner is initially presented with a MPLevel for SHO (in Figure 8.2, the interface at the left hand side) that is later exchanged with a more complex level for oscillation with friction (of which the interface can be found at the right hand side). The second, more complex level adds a variable (friction) to the previous level. In consequence, in the graphical interface for SHO, the learner can manipulate the input variables string constant $k$ and mass $m$. In the interface for DO, additionally the friction coefficient $c$ can be manipulated. For both interfaces, of the state variables the flow variables displacement and velocity only are shown. The interfaces thus provide a motion perspective.

A final remark concerns the presence of a structural perspective. The author of SETCOM not only provided an evolution of the learning environment in terms of the variables present, he also provided an evolution in representations of device structure. For each MPLevel, the author created a diagram representing an example device, that is, a mass-spring device for SHO and a mass-spring-damper device for DO. The SETCOM example reveals that, with a simple-to-complex progression of behavior, device structure may evolve too. The diagrams of device structure can be considered to be representations of a structural perspective. Hence, in the SETCOM a structural perspective is permanently connected to a behavioral perspective.

In chapter 7 it was remarked that one of the flaws of the original MP approach was the lack of an explicit notion of structural perspective (section 7.3.3.1). SETCOM illustrates one solution by providing a structural perspective within a MISLE. The presence of a structural perspective and the connection of that perspective to behavioral perspectives is recognized as important (section 7.2.2.3). However, the authoring tools for model progression described in the following section provide no conceptual support for such a connection.

## 8.3 Authoring tools

As was sketched in section 8.2.1, the construction of an MPLevel in SMISLE is essentially the creation of a *variable filter* (MPFilter) and *state settings*. The creation of an MPFilter should be supported by authoring tools. The intention was to provide: 1) a plain editor (MPEditor) that could provide technical support for the creation of MPFilters, 2) a tool that could provide conceptual support on how to construct instructionally valid MPFilters. This latter Model Progression authoring Tool (MPTool) should 1) provide advice on the construction of multiple MPFilters on the basis of an awareness generic elements of SMISLE models and 2) allow to define in which order these could best be explored by the student.

### 8.3.1 The MPEditor

Instantiation of an MPFilter meant setting a selection on the variables of a simulation model. The MPEditor displays all variables of a specified simulation model and supports selection. The screendump in Figure 8.3 shows the MPEditor instantiated with the variables of a model of simple harmonic oscillation. The input variables (in the left column) are those variables that can manipulated by the student. State[2] and output variables are found in the right column.

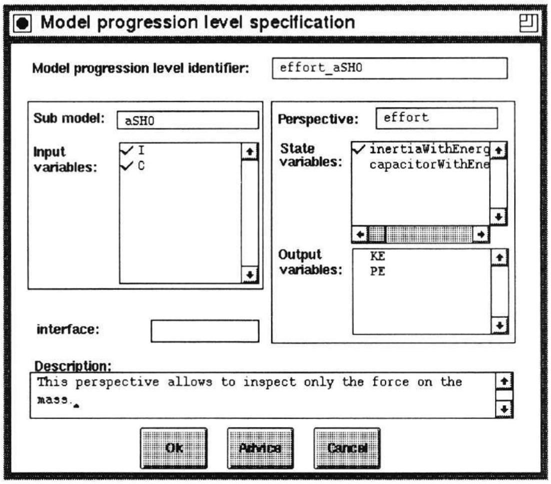



Figure 8.3: The MPEditor, instantiated with the variables of the sub model of simple harmonic oscillation

[2]The labels for the state variables are generated and, unfortunately, not very meaningful. The labels stand for 'velocity' and 'force' respectively.

**Simple-complex levels** At the simple-complex dimension, an MPFilter is created by deselecting input variables. From a complex simulation model, a less complex MPFilter[3] is created by 'hiding' input variables. From a model of DO, a submodel for SHO can be approximated by deselecting the variable 'friction' and setting its initial value to 0[4]. Secondly, if submodels that differ in complexity are present, these submodels can be defined to act integral as MPFilters.

**Perspectives and derivation-based views** Each submodel may be investigated by the student from different perspectives. A perspective is determined by deselection of state and output variables. Derivation-based views can be created in exactly the same way. In this editor, for instance, one might deselect all variables but displacement and velocity to create a motion perspective. Similarly, one might, for instance, deselect all but the displacement variable to create a 'derivation-based view' on displacement.

**Progression** The support provided by MPEditor is mainly technical. In its current implementation, the MPEditor supports the creation of filters, with or without conceptual support from the MPTool. With respect to progression, the order in which levels should be presented to the student has to be defined using SMISLE's enabling conditions editor (see King *et al.*, 1995).

## 8.3.2 MPTool

Basically, the MPEditor provides all functionality needed to instantiate MPFilters. In many cases this will not be sufficient to create a valid form of model progression. Model progression may be understood as a vague notion, however, many authors will be lost when required to impose model progression upon their simulation models. Hence, the need for conceptual support was anticipated.

The intention of MPTool is to provide support for the instructional design of model progression. The exercise as described in chapter 7 aimed at generating a basis for such conceptual support. Conceptual support implies showing authors what series of simple-complex MPLevels could be like for their domain and what might be potential perspectives upon their domain. This is exactly what MPTool does.

MPTool provides suggestions in the sense that it, for instance, indicates potentially valid perspectives and shows which state and output variable should be selected to create a certain perspective. The suggestions are in all cases materialized by showing a suggested instantiation of an MP-Level in the MPEditor. It is then up to the author to accept that level, modify or reject it.

### 8.3.2.1 The creation of levels

**Levels at the simple-complex dimension** As described in section 7.5.1.1, complexity was operationalized in terms of the number of input variables of the model. Hence, the MPTool analyzes the set of available models[5] and attempts to find simple-complex pairs of models. That is, it searches for pairs (**a-b**) of models where **a** contains a subset of the input variables of **b**.

[3] In the interface named 'Sub model'

[4] This cannot be done directly in the MPEditor. Setting of initial values is done in SMISLE's *initial state editor* that is linked to the graphical interface editor.

[5] It should be noted that the above sketched tool uses currently available submodels and tries to find out whether these vary in complexity. A, not yet implemented, alternative option is to take a complex model and literally hide (input) variables.

Figure 8.4 shows the MPTool with at the left hand side a list of pairs of simple-complex models for the domain of oscillation. Amongst other things, models for SHO, DO and FDO are present. MPTool allows the author to choose from all imaginable combinations. In this example, not only SHO-DO and DO-FDO, but also the pair SHO-FDO appears in the list. This is to remind authors that they are allowed to define a progression of levels so that not all intermediate levels need to be studied by the student.

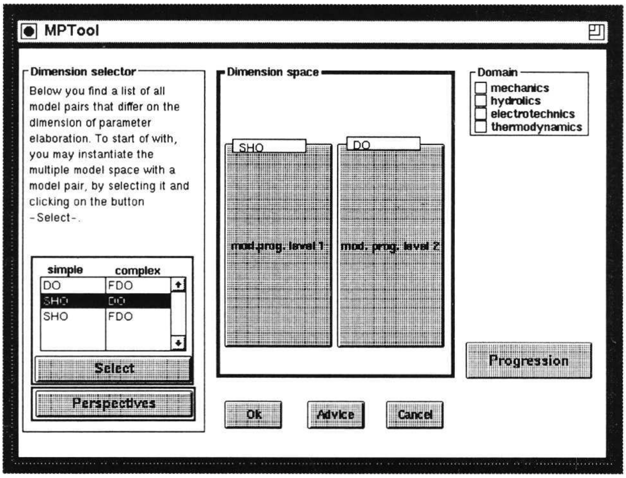



Figure 8.4: The MPTool with in the left-hand side column suggestions for simple-complex combinations

The 'Dimension space' in the center of the window can be instantiated with one of the pairs from the list. After inspection of the contents of a submodel by means of the MPEditor (see section 8.3.1), a submodel can be accepted as a whole to act as MPLevel. This implies that all perspectives on the submodel, thus all state and output variables, will be open for inspection by the student.

**Levels for perspectives** If desired, the author can decide to create MPLevels that include a single perspective on a model. To define perspectives on models, an option 'perspective shift' activates icons for flow, effort and energy perspectives in the dimension space. With information on the nature of the domain, the abstract terms of 'effort' and 'flow' are translated to domain level terms, such as force and motion (see Figure 8.5). This is done by using the specialization links as present in the in section 7.4.4 sketched framework.

On the selection of one of the perspectives, the MPTool retrieves the associated state or output variables. It activates the MPEditor for inspection of the MPLevel that was just suggested. If the suggestion is accepted, an MPLevel is created. Obviously, not all separate perspectives on every submodel need to be accepted. It is up to the author to decide on a sufficient set of MPLevels.

**Levels for derivation-based views** An even finer grained distinction can be made within the 'flow' and 'effort' perspective. For the flow perspective the views 'displacement' and its derivative

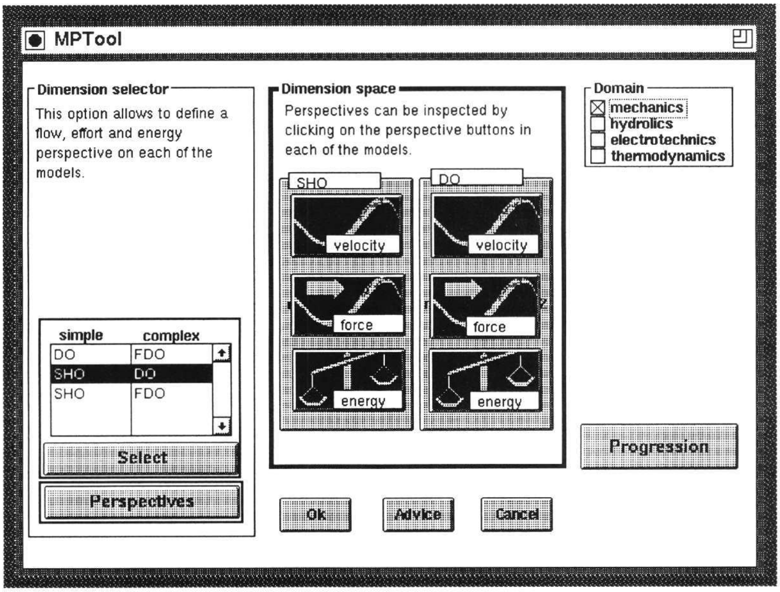



Figure 8.5: MPTool: perspectives

'flow' are present and for the effort perspective te views 'momentum' and its derivative 'effort'.

#### 8.3.2.2 Defining progression

Once a number of MPLevels have been created, a next step is to define the order in which MPLevels will be shown to the student. The specification of progressions is supported by a progression editor, as visualized in Figure 8.6.

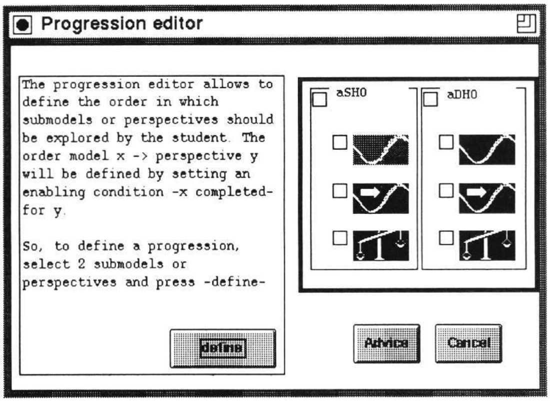



Figure 8.6: The progression editor

In this editor, progressions are defined pairwise. Progressions from perspective to perspective can be defined, submodel to submodel but also submodel to perspective and vice versa. In SMISLE the activation of instructional measures is controlled by a mechanism that uses so called 'enabling conditions'. Hence, the definition of a progression for pair **a-b** automatically instantiates an enabling condition on **b**, indicating that '**a** must be completed' before **b** can be activated.

The suggestions for progression as discussed in section 7.5.3 are to be included in the SAM, SMISLE's Advice Module (de Jong *et al.*, 1995c). This module is linked to the authoring system and provides advice on instructional design decisions.

## 8.4 Evaluation

The intention of the exercise of the previous and present chapters was to provide authors with *technical* as well as *conceptual* support for the construction of model progression. A main question to ask is whether the technical support implemented in MPEditor and the conceptual support as present in MPTool effectively support the construction of model progression. In this section an attempt will be made to answer this question. To assess whether support is effective, several aspects in support have to be considered. A first question that should be posed was that of the **validity of the operationalization** as provided by MPModel.

A first prototype of the MPTool provided us with an instrument that enabled experimentation with the operationalization (MPModel) of model progression, as was sketched in chapter 7. MPTool could be used to generate suggestions based on MPModel for a variety of domains. Hence, MPTool might be applied as an instrument to assess the validity of MPModel.

If the operationalization in MPModel was judged valid, a second question could be posed; can the MPTool **effectively support** inexperienced authors in creating a valid form of model progression? A problem that might obscure the results could be an inadequate implementation. As observed in an earlier exercise in evaluation of the authoring environment in SMISLE (Kuyper *et al.*, 1995), it was all too evident that a first prototype would barely be adequate. Therefore, efficacy could not be judged separate from the **adequacy of the implementation**.

### 8.4.1 Method

An evaluation study was performed to assess the adequacy of the implementation, the validity of the operationalization, and efficacy of the conceptual support. This study was conducted by van Rijswijk and is more elaborately reported in (van Rijswijk, 1996)). The study was set up to be exploratory in nature. Its intention was to generate as much information as possible on the intentions, behavior, and demands of authors, rather than to test strictly defined hypotheses.

The following aspects were subject to study:

- **The adequacy of the implementation** The adequacy of the implementation was to be analyzed by observing both experienced and novice authors work with the MPEditor and MPTool while completing a model progression construction task.

- **The validity of the operationalization** The validity of the operationalization was to be assessed by having experienced authors design model progression without, and subsequently with the support of the MPTool. Discussion on differences between the results of both tasks should result in expert author's judgments of the validity of the operationalization.

- **The efficacy of support** Some indication of effectiveness should be achieved by comparing the results of by MPTool supported construction of model progression by experienced authors with the results by novice authors.

**Subjects** The efficacy of support was to be assessed by comparing the achievements of experienced authors and those of novices. We therefore recruited: 1) authors that were inexperienced in teaching or instructional design ($N = 8$, labeled as $in_1, \ldots, in_8$), and 2) authors that had teaching experience in the experimental domain ($N = 4$, labeled as $ex_1, \ldots, ex_4$). All authors had to be familiar with the domain used in the experiment.

**Procedure** The authors of both groups were given the assignment to create model progression for the domain of oscillation. The target group for which the simulation environment should be designed was high school students. Both groups of authors received an identical instruction concerning the model progression construction task. The notion of model progression was explained in very general terms and was illustrated by means of an example from a procedural domain. This illustration domain was chosen to be procedural to avoid analogical reasoning with the conceptual domain used in this study.

The model progression construction task was performed three times with varying levels of authoring support. Initially, neither technical nor conceptual support was provided (*the paper task*). The paper task was followed by a second task (*the MPEditor task*) where mainly technical support was provided. In this second task, the subjects were provided with an overview of available variables as present in the MPEditor. A final task (*the MPTool task*) was one where conceptual support as present in MPTool was added. The overall procedure took two and a half hours per author. Below, we will elaborate on the instructions provided in the various tasks.

**The paper task** For the paper task, the authors were provided with a set of ideal device components that they could use to construct simple devices. For the oscillation domain, the authors were provided with a mass, a spring, a damper (i.e., an element that models resistance) and a component that could make a harmonic force act on the mass. All device components were instances of bond graph n-ports (see section 7.4.4). Each building block was accompanied by a list of variables that could be used to model the behavior of the device components.

The subjects were asked to construct a series of simple-complex devices on the basis of the components available. For the behaviour of each of the devices, they were required to indicate which variables should be open for manipulation and/or investigation. Subsequently, they were asked to indicate essential perspective on the behavior of the devices. More specific, to tell which variables they would like to show to learners in one or more graphs.

**The MPEditor task** For the MPEditor task, all variables used to model the most complex device were given. The authors were informed that they could create MPLevels for simple-to-complex progression and perspective shift by deselecting variables from those present in the MPEditor. The analogy with variable selection as in the paper task was made explicit. No further information was given.

**The MPTool task** For the tool task, the SMISLE was provided with a series of models. The MPTool thus provided a list of simple-complex pairs of models. The authors were provided with information on the working of the tool upon request only.

**Task order considerations** It should be noted that the order in which the various tasks were to be performed might have affected the outcomes of this study. A reverse order may have lead to different results, in particular for the MPTool task.

The current order was chosen so that it best reflected a design life cycle. Tools such as MPEditor and MPTool should never be used at the start of the design trajectory. Tool use should be preceded by a design stage. Such a design phase might be comparable to our paper task. With respect to model progression, in an early design phase the author should reflect on the rationales to be applied, on the level from which to start. Only those authors that do not have a clue with respect to rationales might rely entirely on the conceptual support provided by the MPTool. For others, the conceptual support may not be more than suggestions and whether these suggestions should be accepted is then entirely up to the author. Having a paper task precede tool use, forces authors to reflect on instructional design before accepting suggestions of a tool. Without such a design phase, suggestions of MPTool might be too readily accepted. Therefore, by the current order we anticipated more fundamental critique on the validity of the operationalization.

**Author's judgment** An elaborate reflection on the tasks and results took place with each author. This reflection ended with a judgment of the adequacy of the current implementation, validity of operationalization, and efficacy of the technical and conceptual support.

In the following sections we will elaborate on the questions posed with respect to implementation, operationalization and support.

#### 8.4.1.1 The adequacy of the implementation

The adequacy of the implementation was to be analyzed by observing the inexperienced authors work with the MPEditor and MPTool while performing a model progression construction task. It should be noted that the 'experience' of the authors was related to their teaching or instructional design experience. 'Inexperienced' said nothing about their computer literacy. To the contrary, some of the inexperienced authors had extensive experience in the use and development of software.

To assess whether the functionality of a tool revealed itself from its interface, authors were given no instruction or guidance unless explicitly demanded for. The author's hesitations, doubts, questions, outcries of desperation, and improper operations were recorded.

These recordings were analyzed in terms of an interpretation scheme of categories of frequently occuring problems in man-machine interaction (see van Rijswijk, 1996). The scheme was based on the work of Norman (1986) and part of it was tested during the evaluation of the entire SMISLE (described in Kuyper *et al.*, 1995).

Major categories of problems are:

- **Erroneous expectations** The author's initial perception of the intentions of the MPEditor and MPTool may deviate from the actual intentions of those instruments. The author might have an erroneous idea of the nature of support provided by the tool or of the global tasks to be carried out to get to a series of model progression levels with progressions defined upon them.

- **Inadequate representations** Representations play a role both in the execution and in the evaluation of activities.
  - With respect to the execution phase, the *'visibility' of functionality* may be insufficient. That is, it may not always be evident from the system interface what operations to perform to achieve a certain goal, in this case, create model progression levels or define progressions. Similarly, users may fail to grasp the order in which to perform the necessary operations.
  - A second issue in execution may relate to the *'visibility of the object of operations'*. As argued in chapter 5, representations should provide a natural mapping to underlying structure.
  - With respect to the evaluation phase, the *'visibility' of results* may be insufficient. Evaluation of the correctness of the author's activities has to be supported by feedback. An analysis of visibility of results thus focuses on whether authors understand and benefit from the feedback provided.
- **Lack of functionality** The functionality of the instruments is considered insufficient if valid actions are not foreseen in the system.
- **Lack of robustness** Lack of robustness refers to the occurrence of unforeseen system errors.

#### 8.4.1.2 The validity of the operationalization

The validity of the operationalization was to be assessed by analyzing the model progression design process and results by experienced authors. Differences between the results of the paper task and those of the MPTool task should provide information on the validity of the operationalization.

#### 8.4.1.3 The efficacy of support

Some indication of efficacy should be achieved by comparing the overall results of experienced authors with those of the inexperienced authors. For the MPTool to be effective, the tool task should with inexperienced authors lead to an improvement of results when compared to the paper task. The quality of the results, and thus the amount of improvement, was judged by taking the results of experienced authors as a norm.

In addition, both experienced and inexperienced authors were asked to give a subjective judgment on the kind of environment (paper, MPEditor, MPTool) they found most suitable for the model progression construction task.

### 8.4.2 Results

#### 8.4.2.1 The adequacy of the implementation

The MPEditor did not cause too many problems for the inexperienced authors. The authors generally managed to construct variable filters without much support. In contrast, the results concerning the adequacy of the implementation of in particular the MPTool were not very promising. We will only list the most fundamental problems. For a full discussion, the reader is referred to (van Rijswijk, 1996).

**Expectations** Few authors initially understood the intention of the MPTool. The text that was meant to inform authors on the intention was not read ($in_1$,$in_2$,$in_5$,$in_6$,$in_8$),[6] or even worse, not understood after reading ($in_3$,$in_4$,$in_7$).

**Visibility of functionality** Once the authors understood the intention of the tool, they had to find out how to create MPLevels. This implied understanding which operations they should perform in what order.

None of the authors managed to perform the appropriate operations to get to a series of MP-Levels without support of the experimenters. Both the creation of simple-complex levels and perspectives was problematic. One of the problems was that authors were unaware of the fact that they were supposed to firstly select a series of models before being able to create perspectives. This order constraint was not evident from the system interface.

**Visibility of the object of representation** One of the possible causes of the authors' inability to perform appropriate operations may have been an inadequate representation of the simple-complex dimension. The pairwise visualization of the simple-complex structure reportedly caused confusion. Only two authors ($in_2$,$in_8$) evidently understood what was meant by this list. A similar observation was made with respect to the representation of the 'dimension space'. The problem with this representation was that it did not provide a full representation of the space. It only showed the two most recently created MPLevels.

After selecting a pair of models, and thus instantiating the multiple model space, four authors ($in_3$,$in_4$,$in_5$,$in_7$) did only use the left hand side representation to create perspectives. From their reactions, it was evident that the pair-wise representation of the multiple model space was inappropriate. Either all perspectives on all models should have been visible or the perspectives on just one submodel should have been visible.

**Visibility of results** The final point had to do with feedback. Newly created MPLevels were to appear in a list in the main menu of SMISLE. Unfortunately the main menu was updated only in reaction to activation, a technical inadequacy that caused much confusion ($in_1$,$in_2$,$in_3$,$in_4$,$in_6$,$in_7$). Feedback should have appeared locally.

**Effects of an inadequate implementation on results** The interaction with the tools was evidently not without problems. It was foreseen that such problems might obscure the results used to judge the validity of operationalization and the efficacy of support.

To be able to judge results of the various tasks, we had to ensure that the authors would be able to complete all tasks. Hence, guidance was provided when necessary. If authors got stuck due to implementation problems, they were helped out by the experimenters. Still, the inadequate implementation may have affected the results.

#### 8.4.2.2 The validity of the operationalization

**Unsupported versus supported task performance** A first step in the assessment of the validity of the operationalization was a comparison of results of the paper task versus MPTool task by

[6] We found a strong relation between the computer literacy of the authors and likelihood of them reading the explanatory texts. Those that were most literate ($in_1$,$in_2$,$in_6$) did not read the texts, whereas the less literate ($in_3$,$in_4$,$in_5$) read the texts.

experienced authors.

If the results from the paper task were not too different from those of the MPTool task, one might conclude that the tool at least allowed to construct valid model progression levels.

In the case of substantial differences, reflection on the differences by the experienced authors should yield insight into the nature of these differences. The experienced authors were to judge whether they perceived the MPTool results to be detrimental or beneficial compared to the results from the paper task.

**Simple-to-complex progression** The two most experienced authors ($ex_1$ and $ex_2$) produced for oscillation a neat series of devices showing progressively complex behavior. The series was exactly equal to the one used in the SETCOM application, thus starting with simple harmonic oscillation (SHO), damped (DO) and forced oscillation with damping (FDO). The authors insisted that they would not change their opinion due to suggestions of some tool. Because of severe time constraints the MPEditor and MPTool were only discussed but not used to create MPLevels.

A third experienced author ($ex_3$) also produced the series mentioned above but added two intermediate models to it, one of which contained a spring with an external force imposed to it and no mass. It should be noted that these two intermediate models are not realistic. In the MPEditor task the author removed the intermediate models from the series. In the MPTool he persisted creating the same series (i.e., SHO, DO, FDO). The fourth experienced author ($ex_4$) initially refused to assume a device oriented approach. She, however, produced on paper a series of graphs displaying displacement against time. A first graph illustrated SHO, a second above critical damping in DO and a third showing both above critical and under critical damping in DO. In the MPEditor, she implemented MPLevel for SHO and DO, and noticed that MPEditor did not allow her to implement an MPLevel that would represent her third level, that of under and above critical damping in DO. She did not add a model of FDO as she judged it to be too difficult for the target population. However, in the MPTool she added the model of FDO as a third MPLevel.

**Perspective shift** $Ex_1$ and $ex_2$ indicated that they had not anticipated perspective shift. Upon request, they suggested the provision of a motion combined with force perspective with an occasional shift to an energy perspective. They affirmed that they considered the suggestions provided by the MPTool worthwhile. An important remark was, however, that they considered it undesirable to treat some of the perspectives in isolation. Certainly, they would never treat a motion and force perspective separately.

In his paper task, $ex_3$ failed to come up with any other perspectives than a force perspective. In his MPEditor task he got confused by the meaningless names of the variables[7] and failed to come up with a perspective choice.

$Ex_4$ already in the paper task suggested all three possible perspectives, motion, force and energy. In the MPEditor, she built two series of simple-to-complex models, the first series was presented by means of a combined motion-force perspective and the second with a combined motion-energy perspective. In the MPTool, $ex_3$ and $ex_4$ created similar linked perspectives. In both cases, these were combinations of motion-force and motion-energy perspectives.

[7]The names of state variables are generated and, unfortunately, were meaningless to authors. To compensate for this, authors were provided with an additional explanation of the generated names.

**Generality** A second step in assessment of the validity should be to move beyond the domain of oscillation. Unfortunately, within the scope of this evaluation study a single pilot only has been done in a different domain. This pilot in the hydrodynamics domain of communicating vessels indicated that for this domain the operationalization could be valid as well. However, to assess the validity of the current operationalization beyond the scope of the domain of oscillation, the present operationalization study should be repeated in a variety of domains.

#### 8.4.2.3 The efficacy of support

**Technical support** Noteworthy is that quite some authors ($ex_4$,$in_1$,$in_3$,$in_5$) noticed that it was impossible to construct MPLevels for super- and sub-critical damping.

**Conceptual support** Without exception, experienced and inexperienced authors perceived model progression to be essential for the design of simulation environments. Their judgment of the efficacy of the MPTool to provide them with conceptual support for the construction of model progression was certainly less positive. Three of the inexperienced authors only prefered the support provided by MPTool or MPEditor. It should be noted that the inadequate implementation can partly be held responsible for the negative judgment.

A more objective judgment should be obtained by comparing the results of experienced and those of inexperienced authors. The results of experienced authors are taken as a norm, the results of inexperienced authors are judged against this norm.

**Simple-to-complex progression** It was concluded from the work of experienced authors in section 8.4.2.2 that the progression SHO-DO-FDO can be seen as a valid progression along the simple-complex dimension. This progression will thus be accepted as the norm.

The experienced authors did not have any trouble constructing the norm progression without support of the MPEditor or Tool. Also, half of the inexperienced authors had no trouble producing the norm progression ($in_1$,$in_3$,$in_4$,$in_5$). Two authors ($in_6$,$in_8$) produced the progression only partly and 2 failed to construct any form of simple-to-complex progression ($in_2$,$in_7$). While working with the MPEditor, 5 authors reached the norm ($in_1$,$in_2$,$in_3$,$in_4$,$in_5$) and the remaining 3 produced at least part of the norm progression. However, $in_2$, $in_6$ and $in_7$ also created levels that are meaningless from an educational point of view. In the MPTool no such levels are created. Here, 4 authors reached the norm ($in_1$,$in_2$,$in_3$,$in_4$). The remaining 4 all skipped one level, 2 of them perceived an intermediate level not necessary for an understanding ($in_5$,$in_8$), 2 left the third level out due to misinterpreting the pairwise simple-complex list ($in_6$,$in_7$).

Table 8.1 lists the results of the inexperienced authors for the various tasks. *Norm* indicates the proportion of authors that managed to produce a series of simple-to-complex MPLevels that satisfied the norm. *Partial* indicates the proportion of authors that only partially produced the norm series. Between brackets can be found the number of authors that created additional MPLevels. *Failure* stands for the number of authors that failed to come up with any such series.

All in all, if improvement of task performance by support from the tools might be noticed, it is in the lower incidence of complete failure.

**Perspective shift** The experienced authors were less unanimous on the perspectives to be used. Generally, motion and force were mentioned to be the most important, yet all mentioned the

Table 8.1: Indication of efficacy of support for simple-to-complex progression by proportion of inexperienced authors that (partially) reached an expert norm

| *Task* | *Norm (add.)* | *Partial (add.)* | *Failure* |
|---|---|---|---|
| Paper | .5 | .25 | .25 |
| MPEditor | .63 (.13) | .38 (.25) | |
| MPTool | .5 | .5 | |

energy perspective to be valid as well. The experienced authors were less clear on which perspectives to apply to which models. $Ex_1$, $ex_2$ and $ex_4$ mentioned the motion, force and energy perspectives in the paper task, $ex_3$ needed the suggestions of the MPTool to come up with an energy perspective. As norm we have assumed the occurrence of all three perspectives, possibly connected.

In the paper task, all inexperienced authors assumed either a motion or a force perspective. Only 2 authors spontaneously mentioned an additional energy perspective ($in_5$,$in_6$). In the MPEditor tasks, just one author reached the norm ($in_2$), others created two perspectives ($in_3$,$in_4$,$in_5$,$in_4$) and two had no idea of what to do ($in_7$,$in_8$).[8] In the MPTool task, 4 authors ($in_2$,$in_6$,$in_7$,$in_8$) created all possible perspectives on all progression models, obviously without considering whether this could useful anyway. Hence, they reach the norm but have chosen a form that burdens the learner with too many models and perspectives. The 3 remaining authors created 2 out of 3 perspectives.

Table 8.2 list the results of the inexperienced authors for the various tasks. *Norm* indicates the proportion of authors that managed to produce a series of perspectives that satisfied the norm. *Partial* indicates the proportion of authors that only partially produced the norm series. Between brackets can be found the proportion of authors that created additional Perspectives. *Failure* stands for the proportion of authors that failed to come up with any series.

Table 8.2: Indication of efficacy of support for perspective shift by proportion of inexperienced authors that reached an expert norm

| *Task* | *Norm (add.)* | *Partial* | *Failure* |
|---|---|---|---|
| Paper | .25 | .75 | |
| MPEditor | .14 | .57 | .29 |
| MPTool | .57 (.57) | .43 | |

The data presented here gives rise to the speculation that instructional design performance of inexperienced authors is improved by conceptual support provided by MPTool. It should, however, be noted that all authors that reach norm performance create a substantial number of perspectives. By just creating all possible perspectives, they reach norm behavior, but also create perspectives that are less desirable. Hence, the conceptual support did not lead to optimal instructional design.

[8]The results of author $in_1$ were removed from this analysis because in this case the support from the experimenters had been too suggestive

### 8.4.3 Conclusion

#### 8.4.3.1 The adequacy of the implementation

The results with respect to the implementation suggest the necessity of a major redesign. For the representation of the dimension space, the current representation was observed to be insufficient. For instance, the pair wise representation of the simple-complex dimension failed to convey its meaning, even worse, caused much confusion. A multidimensional structure should, whenever possible, be visualized as a multidimensional structure.

For the implementation of the authoring tools, it was decided to use a subset of the SmallTalk library, as was available in the UI builder VisualWorks. This was done to minimize the effort to be spent on implementation. This choice severely limited the means for displaying information and designing interaction. Standard graphical objects such as windows, various buttons, text fields, list and matrix displays could be used. However, no facilities for dynamic generation of graphical representations were available. This restriction manifested itself in the inability to generate the multidimensional structures needed to represent a model progression dimension space. As the dynamic generation of multidimensional structure was assumed necessary, the restriction of staying within the VisualWorks library should be abandoned.

With a single representation of the model-perspective dimension space it should be possible to reduce the number of actions necessary to obtain a 'visible' result. With this we have arrived at a second issue, that of supporting the operations to be performed within the MPTool.

The MPTool should more readily reveal 1) which operations should be performed, 2) the order in which operations should be performed, and 3) what the results of those operations were. Which operations should be performed is more easily understood if all operations act upon a single structure, that is, the series of simple-to-complex submodels with, within the submodels, the potential perspectives. Therefore, again, no partial and distributed representations of that structure should be allowed anymore.

With respect to the order in which the operations should be performed, the tool should provide procedural support by enhancing context sensitive hiding of functionality. This might, however, reduce flexibility in development. One might, therefore, think of an expert mode that would provide more flexibility.

A final conclusion concerns feedback, feedback should be local. It should be provided within the tool and not only in some central menu. The final section 'revision' shall focus mainly on suggestions for improvement of implementation.

#### 8.4.3.2 The validity of the operationalization

In contrast to the results of the evaluation of the implementation, the results of the evaluation of the operationalization do not give rise to rejection and only to minor revisions. For the creation of a series of simple-to-complex MPLevels in the domain of oscillation, the suggestions of MPTool were likely to lead to a similar series of MPLevels as those created by experienced authors. For the definition of MPLevels for perspectives, we may conclude that for oscillation the suggested perspectives are valid. However, an important result from this study is the observation that experienced authors will not readily present effort, flow or energy perspectives in isolation. For oscillation, the combination of a flow-effort or flow-energy perspective seems to be prefered over the presentation of isolated perspectives. Hence, what we have learned from the evaluation is firstly that the MPTool should not guide the authors to create such isolated perspectives, as it does now. The MPTool should thus:

- **facilitate the combination of perspectives** rather than the selection of isolated perspectives.

Secondly, the observation that several authors tried to create MPLevels concerning super- and sub-critical damping once more underlines that an MPLevel should be more than a filter on variables. Hence:

- An MPLevel should include settings of initial values and thus **add state setting to a variable filter**.

It should be noted that the current evaluation is not sufficient to conclude that the operationalization is valid. This study merely suggests that principles derived from analysis of written material are likely to be useful in the instructional design of environments for exploratory learning. That is, the principles derived from written material on oscillation were to a large extent suitable for the construction of model progression in that domain.

An assessment of the validity of the operationalization demands for a replication in a variety of domains of the study on paper and MPTool design by experienced authors. The exercise in the domain of communicating vessels indicates that the current operationalization may lead to a valid form of model progression for this domain. For instance, the flow (volume flow) and effort (pressure change) perspective represent core notions in the high school curriculum on hydrodynamics. The energy perspective seems slightly less relevant than in the oscillation domain, but is still incidentally provided. Yet, further analysis in a variety of domains is necessary to justify the conclusion that the current operationalization generally leads to a valid form of model progression.

#### 8.4.3.3 The efficacy of support

To get an impression of efficacy of the support provided by MPEditor and MPTool, paper, MPEditor and MPTool results of inexperienced authors were compared to a norm. Due to the limited amount of data it was not possible to make any conclusive statements on differences in task performance. With respect to simple-complex levels, no clear improvement was observed. With respect to the creation of levels for perspectives, the data show a trend towards improvement due to the conceptual support by the MPTool as a larger proportion of authors reach norm behavior. However, one danger of support of the kind provided by MPTool should not be left unnoticed. In the MPTool inexperienced authors readily create a large number of perspectives without considering the implications of presenting all these perspectives to students. Things can be made too easy.

### 8.4.4 A proposal for revision

**The implementation** The representation of the dimension space, visibility of functionality and feedback of the MPTool need substantial improvement. With respect to the representation of the dimension space, the intentions of the MPTool may be more readily conveyed by trading the current simple-complex level pair-list and the pair-wise perspective overview for a visualization of the complete instantiated dimension space as in Figure 8.7. Now, construction of model progression would just be the dragging-and-dropping of potential MPLevels on a scenario.

The interface sketched here is a direct manipulation interface. With this, the 'conversation' metaphor, as applied in the previous interface, is traded for a 'model world' metaphor (cf., Hutchins

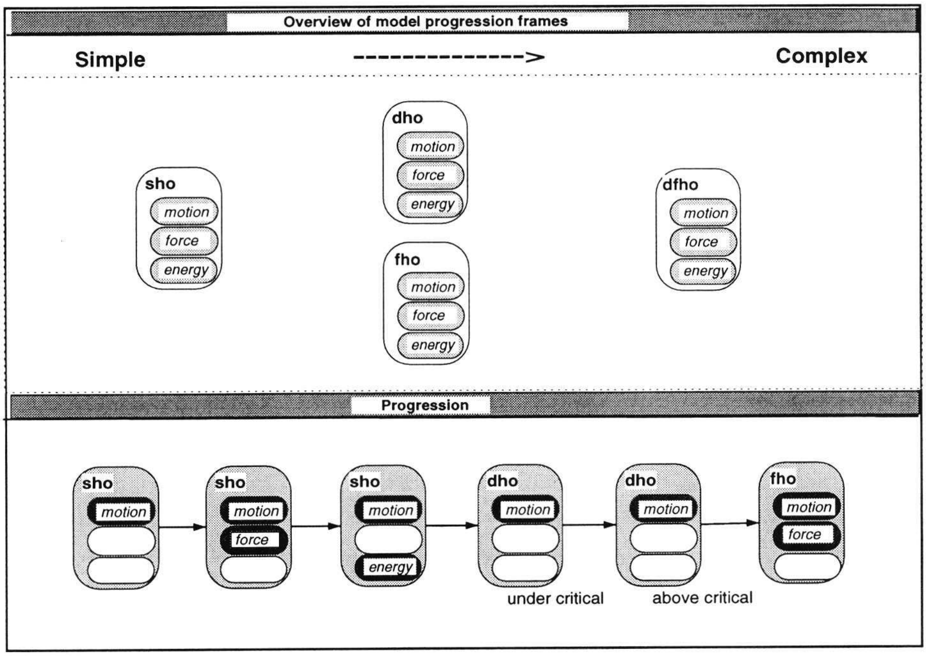



Figure 8.7: A revised interface for the MPTool

*et al.*, 1986). The 'world' of interest, that is, the potential MPLevels and their simple-complex and perspective shift relations, is explicitly represented and the user directly interacts upon this world.

The application of a world metaphor has several advantages. Firstly, selection of MPLevels and progression specification is now achieved by means of a single operation. In the previous prototype, the same goal was achieved by a series of at least 4 operations. Secondly, the order restriction, first having to select simple-complex levels before being able to create perspectives, is removed. Thirdly, the expectation is that the revised representation provides a more *natural mapping* to the underlying multidimensional structure. Finally, with regard to visibility of *results*, results of the selection actions will be directly visible in the 'scenario'.

**Non directive support for instructional design** Some principles on guidance by graphical layout manipulation from chapter 5 can be reused to guide the construction of a valid sequence of the MPLevels. For example, the horizontal dimension can be used to reflect the complexity of the models. That is, to tacitly guide simple-to-complex ordering for presentation, simple models should be displayed to the left of the more complex models. This left-to-right order is likely to support the choice of an instructionally valid (simple-to-complex) order (see chapter 5).

**Unresolved issues** A problem still to be tackled is how to prevent inexperienced authors from creating too many MPLevels. A next version of MPTool should at least incorporate warnings for authors to be sparingly with MPLevels.

Further study of behavior of experienced authors might lead to heuristics for more conceptual support on the selection of MPLevels. The current data on perspective selection by, for instance, experienced authors, suggest that some perspective types are selected more frequently than others. In the oscillation material, the motion perspective is used as the connection between all MPLevels at the simple-complex dimension. Force and energy perspectives are selected far less frequently. It could be the case that a perspective that reveals concrete, observable behavior should be seen as a base perspective. With a base perspective permanently present, more abstract perspectives (force and energy) might be linked to this base perspective when learning goals promote such selection.

Various perspectives could have various functions. It might be worthwhile to study the incidence of flow, effort, and energy perspectives in a variety of domains, in written material or by having experienced authors create model progression.

# Experiment: The effects of model progression on learning 9

This chapter documents the joint work of Wouter van Joolingen, Anja van der Hulst, Janine Swaak, Ton de Jong and Robert de Hoog and is an adapted version of SMISLE Deliverable D24a:

*Van Joolingen, W., van der Hulst, A., Swaak, J., de Jong, T, and de Hoog, R. (1995). Support for simulation-based learning; the effects of model progression on learning about oscillatory motion. University of Twente: Twente. Deliverable D24a,* DELTA, SMISLE *(D2007).*

The learning environment used in this study was developed by van Joolingen (see van Joolingen *et al.*, 1995) and the tests were developed by Swaak (see Swaak, 1995).

## 9.1 Introduction

In chapter 1 we have addressed the potential benefits of exploratory learning environments. Such environments allow learners to engage in a process of active knowledge construction that was argued to result in deeper rooted, more flexible knowledge. We have also listed problems observed in exploratory learning. Multiple studies in the field of simulation report highly unsystematic approaches, summarized under the label 'floundering'. These problems were hypothesized to be due to an inability of students to effectively perform the tasks necessary for fruitful exploration.

It is this problem that is tackled in the SMISLE project. SMISLE addresses the integration of instructional support in simulation-based learning environments. The mission is to overcome some of the problems associated with exploratory and discovery learning by offering the learner various means of instructional support. Model progression is one of those means. As argued in chapter 4, model progression could potentially be a fruitful means for support of information space exploration.

In SMISLE the necessity of support for exploration was well recognized. Designing effective support for exploration is, however, not trivial. Many measures that had been tried before failed to show beneficial results (see e.g., de Jong *et al.*, 1995c; van Joolingen & de Jong, 1993). Therefore, each measure proposed in SMISLE was to be thoroughly tested in various contexts. This chapter describes one of the experiments that was set up to assess the efficacy of the current implementation of the notion of model progression.

The domain used in the experiment was again oscillatory motion. For this domain a learning environment (MISLE) was developed, which was called SETCOM: System for Exploratory Teaching of a Conceptual model of Oscillatory Motion. This system was developed by van Joolingen and described in (van Joolingen *et al.*, 1995). In the present study, two versions of SETCOM were compared, one with and one without model progression. In this latter version, learners were confronted with a complex model right from the beginning. But, before discussing the study itself, we will make a brief sidestep and discuss some experiences with implementations of model progression.

### 9.1.1 Model progression, experiences

The notion of model progression was only recently introduced in the field, but triggered a lot of activity in structuring simulations in the form of a series of models. To name just one example, the simulation NEWTON (Teodoro, 1992) provided a nice example of simple-to-complex progression in the domain of kinematics. Within a simulation of motion of point-masses, the simulation evolved step by step from ideal, frictionless motion, to motion with friction, to motion under gravity. Simultaneously, the options for inspecting the behavior of the point mass were extended, from a one dimensional representation via a two dimensional vector representation and finally to a numerical representation.

Where many have described designs that implemented a form of model progression, little is done to assess the merits of the approach. One exception that must be quoted from is a study by Veenman and Elshout (Veenman, 1993; Veenman & Elshout, 1990). In this study part of the Electricity lab as described in the work of White and Frederiksen (see e.g., White & Frederiksen, 1990) was reimplemented and used to experiment with model progression on the qualitative-quantitative dimension, or the precision dimension (see section 7.2.2.1).

The experiment failed to reveal any benefits of model progression on the dimension of precision. No differences in learning effect due to model progression could be established. Moreover, the subjects in the model progression condition spent twice as much time as a control group that worked with the highest order level only (208 versus 118 minutes). These results indicate that the model progression condition used here was not more effective and certainly less efficient than the condition without model progression.

The experiment described in the present chapter addressed model progression along a different dimension, the simple-complex dimension. In the following section we will first refer back to the claims that were made with respect to the potential benefits of an application of such model progression.

## 9.2 Model progression, claims

Model progression aims at facilitating the task of self regulation. Instead of confronting learners with the full complexity of a target model, they are provided with a series of less comprehensive models that aim at establishing a connection to prior knowledge and progressively introduce more complexity.

The approach suggests the realization of an environment that provides support at a global level (i.e., between MPLevels) but leaves freedom at a local level (i.e., within an MPLevel) and with that allows learners to be actively engaged in learning while not putting them at risk of loosing control. Regulation at a local level is assumed to be enhanced by the introduction of only few new elements at a time. That is, if model progression is designed appropriately, most of the content of a new level is already known, and as shown amongst others by Shute and Glaser (1990), the more students know about a model, the better they manage to regulate their exploration (see also chapter 2).

### 9.2.1 Hypotheses

The hypothesis resulting from these claims is that model progression will lead to an enhanced regulation, manifesting itself in less chaotic exploratory behavior. The behavior that was previously named 'floundering' (chapter 1). As in part B, it was expected that knowledge gain from a more methodic exploration would be reflected in an increase of knowledge of relations among concepts (structural knowledge) rather than in increase of knowledge of concepts themselves (previously named 'definitional knowledge').

Hence, the following hypotheses are investigated:

- *Model progression improves the quality of information space exploration.* Model progression ensures that with each next model progression level the learner is confronted with only a small number of new variables and relations. Therefore, most of the content of a next level is already known to the student. Such extensive prior knowledge is thought to make regulation of exploration easier (see section 1.2 and the discussion of the 'Matthew effect' in section 2.3.2.3). Enhanced regulation should be manifest in less 'floundering' (section 1.1). Students were expected to more systematically manipulate variables before going on to the next input variable. Enhanced quality of manipulation should therefore be manifest in less isolated changes to variables.

- *Model progression will enhance the number and improve the quality of relations explored.* Complex models can 'hide' relations. For instance, in the oscillation domain, the simple relation between force constant and frequency can be found at any level. However, finding such a relation may be easier if less variables are present.

- *Model progression reduces the load on working memory.* With only a small number of new variables to be introduced at a time, increased manageability should also manifest itself in the student's perception of cognitive load.

- *Model progression allows to build upon prior knowledge.* Model progression was thought to facilitate a gradual accumulation of knowledge. For understanding, for instance, the phenomenon of resonance, one must first understand that harmonic systems have a natural fixed frequency, the eigenfrequency. Thus, the notion of eigenfrequency must be mastered before it makes sense to investigate the phenomenon of resonance. The simple-to-complex sequence of models as implemented in SETCOM is thought to facilitate such accumulation of knowledge. Consequently, the gain of model progression should be in acquisition of the more complex notions present in the higher model progression levels.

- *Model progression results in deeper and more intuitive knowledge.* Since model progression allows the learner to study relations in isolation first, and then in full complexity, the various aspects of the relations found can be stored in a more structured manner. This implies that the knowledge should be better and faster applicable in various situations, especially when those situations are relatively simple and qualitative.

The next section describes the empirical study in which these hypotheses were tested.

## 9.3 Method

The study described here aimed at measuring the effects of model progression along the simple-complex dimension. To this end, two versions of a simulation learning environment were created, one with model progression and one without. Subjects were engaged in a session with one of these two environments. Before and after this session they received tests measuring definitional and propositional knowledge (see section 9.4). During the session, the subjects' actions were recorded in a log file. These log files allowed to study the exploratory behavior and with that the extent to which exploration could be judged as 'floundering'. During the session, subjects were queried on their perceived cognitive load and perceived difficulty of the subject matter.

### 9.3.1 The learning environment

The learning environment that was used in this study is called SETCOM (System for Exploratory Teaching of a Conceptual model of Oscillatory Motion).

In brief, SETCOM employs simple-to-complex model progression. The learning environment starts with a model of a simple device, a mass suspended from a spring, and adds two levels of increasing complexity by introducing a damper and an external force. A fourth level includes the application of notions from prior levels in a more realistic setting. This final level does add complexity, but is not considered to be part of the model progression sequence, since the simulated system is fundamentally different from the ones introduced in the first three levels. Thus, in the first three levels, variables and relations are gradually introduced through a simple-to-complex model progression, the fourth level shows an application of the oscillation theory in a more realistic setting. It was decided that this level remained available for all subjects, but was not used as part of the model progression.

In addition to model progression, the SETCOM provides support in the form of **assignments** and **explanations**. Assignment may, for instance, require the learner to make a statement on the nature of a relation between two variables, or ask for a prediction of the effects of a change of an input variable. Explanations are statements that explain the nature of the variables present in the simulation. In all cases it was up to the learner to decide whether or not to use assignments and/or explanations. The nature of the support provided by SETCOM is more elaborately described and also illustrated in (Swaak *et al.*, 1996).

### 9.3.2 Conditions

The experimental group that received model progression worked with the original SETCOM. The group receiving no model progression worked with a version in which the two lowest levels (simple harmonic, and damped oscillator) were removed. All assignments and explanations for these levels were moved to the forced oscillator level. This means that all students received the same set of assignments and explanations, the only difference between groups was the presence of the first two model progression levels.

### 9.3.3 Subjects

Twenty-eight subjects participated in the study. They were undergraduate students in mathematics/informatics, chemistry, and psychology. The students from these different groups were equally distributed over conditions ($N = 12$ for the model progression condition and $N = 16$ for the non model progression condition). All subjects had studied physics including classical mechanics.

## 9.4 Data collection

### 9.4.1 Product measures

To assess the learners' knowledge gain, a series of three tests was used. 1) A so called definitional knowledge test aimed at measuring subjects' knowledge of concepts. 2) A test for compiled propositional knowledge intended to measure the subjects' 'intuitive' knowledge of relations. This test measured whether subjects were capable of applying their knowledge of relations (propositions) to new problems. 3) A test for non-compiled propositional knowledge aimed at measuring the subjects' articulate knowledge of relations in the domain.

The test for definitional knowledge and that for compiled propositional knowledge were presented as pre and posttest; the propositional knowledge test was presented as posttest only. For the definitional knowledge, the same test was used as pre and posttest. For compiled propositional knowledge, parallel versions were used.

#### 9.4.1.1 Definitional knowledge

The tests for definitional knowledge were concerned with the knowledge of individual facts and definitions of concepts and variables present in the simulation. Most of the definitions and facts had been given in the explanations. Besides, with a thorough understanding of the behavior as captured in the simulations, the concepts should be understood well and definitions might be derived.

Definitional knowledge was measured by means of multiple choice items (presenting three answer alternatives). The test originally consisted of 30 items.

#### 9.4.1.2 Propositional knowledge

In the experiment described in chapter 6 investigating the knowledge acquired from exploration in a hypertext environment, two types of structural knowledge were measured, so called 'propositional' and 'configural knowledge' (section 6.3.1). In the pilot for the current experiment a similar cardsort task for assessment of configural knowledge was administered. It turned out, however, that clusterings on the basis of superficial features of concepts could not be discriminated from clustering on the basis of a true understanding of the phenomenon of oscillatory motion. Due to the perceived inability to produce a sufficiently discriminating concept set for a cardsort task, no such test was administered.

On the other hand, propositional knowledge was measured in two forms, a compiled and a non-compiled form (see e.g., Van Berkum *et al.*, 1991). Non-compiled knowledge refers to knowledge that allows to make articulate statements on the nature of relations. Non-compiled knowledge requires interpretation if this knowledge has to be applied to explain or predict a novel situation. In contrast, if knowledge of relations is compiled, it is more implicit and it is more effortlessly applied to new situations. Compiled knowledge is frequently hypothesized to be a result of learning by induction (see the discussion by Swaak (1995)).

It is this inductive type of learning that is prevalent in simulations. Relations need to be induced by manipulating the simulation. In contrast, in hypertext, knowledge of relations does not have to be induced from the material, usually this knowledge is given. In the experiment with a hypertext environment described in chapter 6, the compiled form was made subject to questioning only. This restriction was made since we were not so much interested in a reproduction of the given. However, for an assessment of learning effects in a simulation context we considered it essential to test for non-compiled knowledge as well. In simulation, non-compiled knowledge is not given, but must be induced from the data.

**Compiled knowledge** For measuring compiled propositional knowledge a test was used that was called the *speed* WHAT-IF *test*. This test was created by Swaak and is described more elaborately in (Swaak, 1995). In the WHAT-IF test, each test item contains three parts: conditions, actions, and predictions. The conditions and predictions refer to system states, which are displayed by means of a drawing of the system accompanied by some text. The action, or the change of the value of a variable within the system, is presented in the text. The WHAT-IF task requires the learner to decide as accurately and quickly as possible which of the predicted states follows from a given condition as a result of the action that is displayed. The items of the task are kept as simple as the domain permits, and the items have a three-answer format. Examples of the test-items can be found in (Swaak, 1995).

Two parallel versions of the test were developed, each consisting of 35 questions. The versions differed in details of the changes given. One of these versions was given as pretest, the other as posttest. These parallel versions were developed to prevent memorization effects. For these tests, not only was the correctness of answers measured but also the response time. Students were instructed to answer as accurately and quickly as possible.

**Non-compiled knowledge** Non-compiled propositional knowledge was measured using a test that asked for statements on the nature of relations between given variables. In this test, learners were confronted with pairs of variables. For each of those pairs, they had to describe the relation they thought to be valid between the variables given. Also they had to indicate if the relation was always valid, or only under certain conditions.

## 9.4.2 Process measures

### 9.4.2.1 Exploratory behavior

All activity of learners while interacting with the simulation was recorded. This provided us with data on the manipulations in the simulation and that on the use of the supportive measures such as assignments and explanations.

**Interaction patterns** With respect to exploratory behavior, we were especially interested in patterns that could indicate regulatory activity, or lack of such activity. Patterns that indicated frequent isolated manipulations of variables were to be considered as manifestations of 'floundering', where patterns that indicated series of subsequent manipulations on single variables were perceived to be manifestations of more carefully planned information space exploration.

The results from the investigation of manipulation patterns were quantified by means of a 'pattern score' (de Jong *et al.*, 1993a). Pattern score is operationalized as the number of times a step was made from changing one of variable to changing another variable, divided by the total number of manipulations. The pattern scores ranges between 0 and 1 with a low score indicating relatively methodic behavior and a high score a more chaotic pattern of manipulation.

**Total number of manipulations** It was hypothesized that model progression might enhance the number and improve the quality of relations explored. The total number of manipulations was taken as an indication of the number of relations explored.

**The perceived need for support** A final measure was the amount of support sought. The subjects were not obliged to do assignments or lookup explanations, rather they were explicitly instructed to decide for themselves whether or not to use these measures. We took the number of assignments and explanations used as an indication of the perceived need for support. Subsequently, if an effect was found it should be analyzed whether this effect was due to differences in support sought.

#### 9.4.2.2 Cognitive load and difficulty

Another type of measurement that was introduced was a measurement of perceived subject matter difficulty and workload (see also Swaak, 1995). At regular moments in time, a small electronic questionnaire appeared that subjects had to fill in before they continued working with the environment. By pulling sliders, they could indicate perceived difficulty of the subject matter, perceived difficulty of the interaction with the environment and their view on the helpfulness of the instructional measures that they had used.

The questionnaire was set to pop up every 20 minutes, but display was always postponed until an event occurred that marked the end of a coherent series of actions, such as closing an explanation or completing an assignment. This was done in order not to let this measurement interfere with learning.

## 9.5 Procedure

Each experimental session had a duration of approximately four hours. In chronological order, the subjects received a brief introduction on the goals of the experiment and were presented with the tests for compiled propositional and definitional knowledge respectively. The tests took a total of 45 minutes.

Having finished the tests, they received a ten minute introduction on the learning environment. In this introduction, the components of the MISLE were explained. These components were the simulation, the assignment, explanation, and model progression screens. It should be noted that the subjects in the control condition also received the instruction on the model progression screen as they had to be able to browse to the fourth level, the level that contained a simulation of a realistic system (see section 9.3.1). All possible operations on those components were shown once. No practice was included in this session.

It should be noted that the introductions of the conditions were different, as each group was shown the interface of the condition (level 1 versus level 3) they were to start with. Following the introduction to the system, subjects were given an introduction on working method and learning goals. With respect to working method, subjects were told to regulate their exploratory behavior. That is, they should decide for themselves whether or not to do assignments, to go over to a next model progression level or to see an explanation. The subjects were told that the learning goal was to discover as much as possible about the model underlying the simulation(s).

The experimenters could give assistance on questions concerning the operating of the environment, but not on the subject matter content. The subjects were encouraged to use the full two hours available for the interaction. Whenever they expressed the wish to stop earlier, they were stimulated to explore more of the environment, however, they were not forced to do so. Halfway through the interaction, a short coffee break was held. Following this break, the subjects were once more instructed on working method. Again it was stressed that they were expected to decide for themselves what support they should seek.

The subjects were not allowed to talk during the session, during the break they had to avoid the subject of simulation. A second restriction was that they were not allowed to make notes. The rationale behind this decision was that we wanted the subjects to use the means only that were provided by the learning environment.

As posttests, again tests for compiled propositional and definitional knowledge were administered. A final test was that for non-compiled propositional knowledge. The experiment was concluded with a discussion on the merits of learning with a learning environment such as SETCOM.

## 9.6 Results

In this section we will first report on the results for the different knowledge tests. Following this, we will give an account of the exploratory behavior and the cognitive load measure. Finally, the relation between exploratory behavior, perceive cognitive load, and knowledge gain will be reviewed.

### 9.6.1 Product measures

**Definitional knowledge** The definitional knowledge test was given in the same form as pre and posttest. It consisted of 30 multiple choice items with 3 alternative answers each. Due to technical problems we did not have the data of the definitional pretest of one student. A reliability analysis on the definitional pretest ($N = 27$; $n = 30$ items) resulted in the removal of one item (of the total number of 30 items) that lowered the total test reliability to a considerable extent. The resulting test reliability was .33 (Cronbach's a). The reliability analysis on the same test used as posttest also resulted in the removal of one item and then yielded a reliability of .60 ($N = 28$; $n = 29$ items). The average number of correctly answered items on the definitional pretest was 15 with an $SD$ of 3 and a range going from 7 to 21 correct items out of 29. On the definitional posttest, the 'number of items correct' scores had a mean of 15 with a $SD$ of 4 and a range from 8 to 25. Table 9.1 gives the average number of items correct for the definitional pre and posttests for the two experimental conditions.

Table 9.1: Mean scores (and $SD$) on the tests for definitional knowledge

| | *Pretest* | *Posttest* |
|---|---|---|
| I (model progression) | 15 (3) | 15 (3) |
| II (no model progression) | 14 (3) | 15 (5) |

In condition I, two students had a lower posttest than pretest score, one student only scored 1 item less, the other 5 items. In condition II, 9 students had less items answered correctly on the posttest in comparison with the pretest, with a range of 2 to 5 less items correct. A repeated measurement analysis on the definitional test-scores showed no significant within-subject effect of number of items correct ($F(1,25) = 1.77, p > .10$). Furthermore, no interaction between experimental condition and test scores was revealed in this analysis.

**Compiled propositional knowledge** For the test for compiled propositional knowledge, items are scored on both the correctness of the answer and on the time used for giving the answer. On the basis of a reliability analysis and an analysis of outliers in response time, a number of items were excluded from further analysis.

Reliability analyses on the WHAT-IF pretest across 28 students resulted in the removal of two items (of the total number of 34 items) that lowered the total test reliability to a considerable extent. The resulting test reliability was .58 (Cronbach's $\alpha$). Reliability analyses on the WHAT-IF posttest resulted in the removal of one item and then yielded a Cronbach's $\alpha$ of .38 ($N = 28, n = 33$ items), a result not very satisfactory. It was speculated that low internal consistency might be explained by differences among subtests. Each test consisted of four subtests, one for each model progression level. However, no differences at sub test level could be detected.

In order to identify outliers in the response times to the WHAT-IF items, regression slopes were computed for every student ($N = 28$) taking the response times on the WHAT-IF pretest items as the independent variable and the response times on the WHAT-IF posttest items as the dependent variable. A response time was defined an outlier if it was more than three standard deviations from the regression slope (a measure related to Cook's distance). We have chosen this method to identify outliers because the regression slopes closely fit our hypothesis, i.e., a decrease in response time is expected between every two parallel WHAT-IF pre and posttest items for each subject. This method furthermore takes into account individual differences. Using this procedure, overall no more than 0.7% of the data was excluded from further analyses.

The number of items over which analyses were done differed between students because the removal of outliers was performed on the basis of individual data. For Condition I an average total, over all students, of 32 items remained, for Condition II this was 32.4 items on the average. Table 9.2 shows the average number of items correct on the pre and posttests for compiled propositional knowledge.

Table 9.2: The average number correctly answered items (and $SD$) on the tests for compiled propositional knowledge

| | *Pretest* | *Posttest* |
|---|---|---|
| I (model progression) | 12 (4) | 16 (4) |
| II (no model progression) | 11 (3) | 16 (3) |

Table 9.3 gives the average completion times (in seconds) of the test issues of the test for compiled propositional knowledge.

Table 9.3: Average completion times in seconds and ($SD$) of the test issues of the test for compiled propositional knowledge

| | *Pretest* | *Posttest* |
|---|---|---|
| I (model progression) | 1027 (212) | 668 (140) |
| II (no model progression) | 1281 (324) | 776 (207) |

We did not find a trade-off between correctness and speed. The correlations found between answer time and correctness had a value of $r = .00$, when computed within subjects across the WHAT-IF pretest items, a value of $r = .00$ when computed within subjects across the WHAT-IF posttest items, a value of $r = -.16$, $p > .10$ when computed within WHAT-IF pretest items across subjects, and finally a value of $r = -.19$, $p > .10$ when computed within WHAT-IF posttest items across subjects.

With respect to the test scores for compiled propositional knowledge, it should be noted that the two groups appear to differ substantially on completion times in the pretest. Also the $SD$'s of the completion times differed considerably across the experimental groups and across the testing conditions. The significance levels of the Levene statistic, computed on the completion times for the WHAT-IF pre and posttest, were, however, large enough to refute the suspicion that the variances were unequal in the two conditions (pretest Levene $(1, 26) = .31$, $p > .10$; posttest Levene $(1, 26) = 2.0$, $p > .10$).

The first analyses performed on the WHAT-IF test scores were repeated measurement analyses. The analyses showed both a significant within-subject effect of number of items correct ($F(1, 26) = 18.34$, $p < .01$) and a significant within-subject effect of the test completion times ($F(1, 26) = 12.93$, $p < .01$). No interactions between experimental condition and test scores were found for both correctness and completion times.

Subsequent analysis was an ANCOVA on the completion times taking the pretest scores as covariate. This ANCOVA showed no differences between the experimental conditions ($F(1, 25) < 1$).

**Non-compiled propositional knowledge** For assessing the performance on the non-compiled propositional knowledge test, two judges scored the completed hypotheses lists of the subjects. This resulted in three different measures (see Table 9.4): the number of hypotheses, the number of hypotheses correct, and the average precision of the hypotheses.

Table 9.4: Average results (and $SD$) for the test for non-compiled propositional knowledge

| | *N of hypotheses* | *N of hypotheses correct* | *Average precision* |
|---|---|---|---|
| I (model progression) | 7 (2) | 3 (2) | 2.6 (.8) |
| II (no model progression) | 5 (2) | 3 (3) | 2.6 (.6) |

Univariate analysis of variance showed that the difference between conditions for total number of hypotheses was significant ($F(1, 26) = 5.4$, $p < .05$).

#### 9.6.1.1 Relations between the product measures

Table 9.5 displays the correlations between the three knowledge posttests over both conditions. For the WHAT-IF test, results are given for correctness of the items and for time separately. For the non-compiled propositional test, the number of hypotheses correct was used.

The pattern which emerges from this analysis is that we find three clear clusters. The first one consists of the definitional test and WHAT-IF correctness, the second one is the WHAT-IF time aspect. The test for propositional knowledge, as measured by means of the hypotheses lists, correlates neither with the first cluster nor with the second one, and could be regarded as a third cluster (the other three propositional knowledge scores show the same pattern of p-values).

Table 9.5: Correlations between the different types of knowledge acquired over the two conditions on the posttest (levels of significance between parentheses)

| | WHAT-IF *correct* | WHAT-IF *speed* | $N$ *of hypotheses correct* |
|---|---|---|---|
| Definitional | .42 ($p < .05$) | .19 ($p > .10$) | .09 ($p > .10$) |
| WHAT-IF correct | | -.01 ($p > .10$) | .01 ($p > .10$) |
| WHAT-IF speed | | | .00 ($p > .10$) |

### 9.6.2 Process measures

#### 9.6.2.1 Exploratory behavior

We registered all the actions learners performed while interacting with the simulation. This provided us with data on the use of the simulation and the supportive measures that were present. Due to a technical problem the log-file of one subject in Condition II was lost. In the subsequent analyses, the interaction data of 27 subjects were used.

**Interaction patterns** A first process measure investigated to which extent the subjects' pattern of interaction could be perceived as being methodical. Patterns that revealed mainly isolated manipulations were considered as manifestations of 'floundering' behavior, whereas patterns that revealed sequences of manipulations on one and the same variable were considered to be manifestations of methodic behavior.

From a close examination of manipulation patterns, it was observed that subjects frequently changed the value of an input variable, yet did not wait to see the effect on the state and output variables. That is, before any effect could have been manifest, a next modification was made. In consequence, a manipulation was taken into regard only if a subject waited a while after a manipulation before making a next modification. Experience showed that it took at least about 8 seconds for the effect of a manipulation to become evident. Hence, only manipulations that were followed by a period without action of at least 8 seconds were accepted to be part of the interaction pattern.

The resulting average pattern score for the model progression condition was .28 ($SD = .09$) and .25 ($SD = .09$) for the non model progression condition. An ANOVA revealed no difference between the experimental conditions ($F(1, 26) < 1$).

**Total number of manipulations** The subjects were rather active in the simulation. Average number of manipulations were for the model progression condition 82.8 ($SD = 33.8$) and 78.9 ($SD = 35.8$) for the non model progression condition. An ANOVA on number of runs yielded no difference between the experimental conditions ($F(1, 26) < 1$).

**The perceived need for support** The learners used the support measures available to them to a maximum extent and hardly any variation between subjects nor conditions existed.

#### 9.6.2.2 Cognitive load

A subject's appreciation of the environment was measured by means of the pop-up electronic questionnaire. Subjects' appreciation of three aspects of the environment were gathered: subject matter difficulty ("is the subject matter seen as easy or difficult?"), system usage ("is working with the system easy or difficult?"), and helpfulness of support ("does support make the learning task easier or more difficult?"). Subjects' scores could range from 0 to 100, where 100 was the 'negative' side, meaning that the subject matter was extremely difficult, the environment was extremely difficult to work with, and support made the task much more difficult. Table 9.6 displays the mean scores (and $SD$) on the three rated cognitive load aspects.

Table 9.6: Mean scores (and $SD$) on the three cognitive load aspects

| | *Difficulty* | *System usage* | *Helpfulness of support* |
|---|---|---|---|
| I (model progression) | 53.4 (9.6) | 46.5 (17.6) | 53.9 (20.0) |
| II (no model progression) | 60.3 (20.1) | 43.3 (23.1) | 48.4 (19.2) |

A MANOVA (taking the three ratings as dependent variables) revealed no differences between the experimental conditions ($F(3,23) < 1$). Subsequent univariate analyses showed no differences on the rating of perceived difficulty ($F(1,25) = 1.9$, $p > .10$) nor on the ratings of system appreciation and on helpfulness of the tools ($F(1,25) < 1$, for both analyses).

### 9.6.3 Relation between product and process measures

#### 9.6.3.1 Interaction pattern and product measures

One of the hypotheses was that methodic interaction should result in enhanced acquisition of knowledge. Correlational analysis, however, reveals no relation between pattern score and product measures, see Table 9.7. Correlations were determined across the experimental conditions. This same table shows a relation between the activity of the student, in terms of number of manipulations, and knowledge of structure as reflected in the WHAT-IF posttest correctness scores and number of hypotheses correct.

Table 9.7: Correlations between knowledge scores and pattern scores and number of manipulations

| | *Pattern score* | *Number of manipulations* |
|---|---|---|
| Definitional posttest scores | -.12 | .30 |
| WHAT-IF posttest correctness scores | .00 | .39* |
| WHAT-IF posttest completion times | -.17 | -.10 |
| Number of hypotheses correct | .23 | .46* |

*: significant at $\alpha = .05$

#### 9.6.3.2 Cognitive load aspects and product measures

Finally, correlations between cognitive load measure and the posttest scores were computed. Correlations were determined across the experimental conditions and we controlled for the three pretest scores. This control was introduced since prior knowledge might have influenced the perceived difficulty. The partial correlations are displayed in Table 9.8.

Table 9.8: Partial correlations between knowledge scores and measures of cognitive load

| | *Perceived difficulty* | *System usage* | *Helpfulness of tools* |
|---|---|---|---|
| Definitional posttest scores | .17 | .33 | .12 |
| WHAT-IF posttest correctness scores | -.04 | .65** | .22 |
| WHAT-IF posttest completion times | .26 | .23 | -.01 |
| Number of hypotheses correct | .28 | .42* | .28 |

*: significant at $\alpha = .05$
**: significant at $\alpha = .01$

Table 9.8 shows that one of the significant correlations can be found for the WHAT-IF correctness scores, indicating that subjects who estimate the system use as easier (low score) have lower correctness scores on the WHAT-IF posttest. The correlation of .42 suggests that subjects who estimate the system use as easier also have a lower number of hypotheses correct.

## 9.7 Discussion

The experiment failed to show an effect of model progression in terms of the differences between posttest scores, both for definitional knowledge and compiled propositional knowledge. Also, subjects in the model progression condition could not give more correct hypotheses than subjects in the non-model progression condition. The only difference was that they mentioned more hypotheses in total. Interaction patterns expressed in terms of a pattern score could reveal no differences in exploratory approach. Finally, even the measures on cognitive load and subject matter difficulty showed no differences. The conclusion seems justified that under the present circumstances, model progression had no effect at all.

In a discussion of the results of the present experiment, a follow up experiment with the SETCOM, conducted by Swaak, van Joolingen and de Jong (1996) plays a crucial role. In this latter experiment, Swaak et al. found a significant effect of model progression for the WHAT-IF correctness scores. The difference between both experiments was that in the follow up experiment the assignments were removed from the learning environment. Under these circumstances model progression was thus found to have beneficial effects. For the experiment described in this chapter, it is inferred that the presence of assignments in the learning environments is likely to have obscured the effect of model progression.

Some words have to addressed to the role assignments played in the exploratory process. As in other evaluations of learning environments constructed with the SMISLE (de Jong *et al.*, 1995a; de Jong *et al.*, 1995b), subjects show that they like the idea of assignments. Nearly all subjects completed most or all assignments. The virtue of this is that assignments seem to have their expected guiding role, in the sense that they get learners going with the simulation. The drawback is that subjects show a tendency to identify the task with completing all assignments. The latter is certainly not the purpose of assignments, they should be a good starting point, not an end-point in the exploration of the simulation. All in all, assignments seem to have a strong guiding role. It is likely that benefits from model progression can be expected only when no guidance in the form of assignments is available.

However, an other aspect that should be taken into consideration is the overall learning effect. In the experiment described in this chapter, subjects did not improve much on the knowledge tests.

For definitional knowledge, there was no gain at all between the pre and posttest, which implies that on the average students did not acquire any formal knowledge during the two hour session. However, for compiled knowledge, there was a small average gain on both correctness and speed.

The overall low improvement on the knowledge tests points to another possible explanation of the lack of effect of model progression. The task of exploring the model and discovering the nature of relations in the model of oscillatory motion was probably too difficult for the experimental subjects. A related explanation may have been that the time available was too short to learn enough to allow the gain scores to be large enough to reveal differences.

In the follow up experiment (Swaak et al., 1996), the subjects were more familiar with the domain. The subjects were first year physics students who had just followed a course on dynamics. Their results show as well little gain for definitional knowledge, but the WHAT-IF correctness scores show a substantially larger gain. Given the beneficial effects of model progression for those subjects, an alternative explanation could thus be that prior knowledge played a role. For the subjects in the experiment described in this chapter, it may have been the case that the subject matter was so difficult that model progression could not really help to overcome the difficulties with the domain.

All in all, model progression will certainly not improve learning under all circumstances. But when no other guidance in the form of assignments is present, model progression may improve learning. Still for some learners, subject matter and environment may be so difficult that model progression is just not enough to overcome the difficulties with the domain.

# Part D

The question tackled in this thesis was how to design environments so that the task of information space exploration remains manageable. Many of the problems in exploratory learning were traced back to high cognitive demands on the learner. The mission of this work was to reduce the burden of exploratory learning, yet retain as much of the benefits as possible. To this end, environments should be designed to allow active engagement and thus enable learners to tailor the learning process to their own needs. Concurrently, these environments should tacitly guide learners to explore in a beneficial way.

Two exercises in non-directive support for exploratory learning had to be instrumental to gain insight in factors that might positively affect exploratory learning. In the final chapter we will look back on the results of both exercises.

# Conclusion 10

## 10.1 Introduction

How to reduce the burden of exploratory learning, yet retain as much of the benefits as possible? This thesis started with a discussion of the potentials, but also of the problems with exploratory learning. It was argued that insufficient regulation of the learning process might well be a major factor in explaining the observed lack of benefits of exploration. The need for 'cognitive tools' for self-regulation was postulated. What manifestation these tools should get was subject to investigation in chapter 2. The intention of the work in that chapter was to come up with requirements for the support provided by these tools. These requirements were derived from insights from the area of instructional science that investigates the effects of measures with respect to sequence.

In short, for information space exploration to be beneficial, the exploratory sequence should aim at establishing a *connection to prior knowledge*. It should reflect essential domain and learning-related aspects of the subject matter. This requirement was labeled *tailored rationales*. A related requirement stated that sequence should be closely related to the structure that acts as rationale, thus be *structure-related*. Finally, to allow learners to adjust their exploratory sequence to their individual needs, any support provided should be *non-directive*, thus facilitate rather than guide.

Currently available prescriptive theory was reviewed in the light of these requirements. It was concluded that the model progression approach as presented by White and Frederiksen came closest to meeting the requirements. The scope of this approach was, however, limited to causal domains. For a general purpose approach, prescriptive theory could provide partial solutions only. Some lacking parts were derived from a bottom up study (chapter 4). This study aimed to generalize from subject matter sequences found in printed material.

Thus, two approaches for the support of information space exploration were proposed. Chapter 4 and 7 each ended with the a description of a prescriptive model. One generally applicable (4), a second tailored to causal domains (7). On the basis of these models, authoring systems were implemented and learning environments generated. These learning environments were used for an experimental assessment of the effects of the support proposed. In the experiments, the focus was on exploratory behavior and on the benefits of the support with regard to acquisition of different types of knowledge. The investigation of exploratory behavior made it possible to judge the effects of the support on the learner's regulation. The assessment of acquisition of the various types of knowledge made it possible to judge to which extent claims on effectiveness of support were valid.

The intention of the work presented in this thesis was to design 'cognitive tools' that would provide non-directive support to exploratory learning. In the following sections, we will look back on aspects of those tools in the light of the requirements from chapter 2.

## 10.2 Connection to prior knowledge

The anchoring of new knowledge to previously acquired knowledge was seen as a main concern. For unfamiliar material, a sequence should be so that new knowledge could readily be connected to knowledge presented earlier in the curriculum. For familiar material, the learner should be allowed to self-organize material so that the new knowledge could readily be assimilated to schemata present in the student's memory.

### 10.2.1 Realization

In section 3.4 it was concluded that means for connecting to prior knowledge were well worked out in the prevailing prescriptive theories in the field. Two design constructs that aimed at connecting to prior knowledge were extracted, advance overviews and iterative cumulation.

- *Advance overviews* present a few fundamental and representative ideas that convey the essence of the entire curriculum. The overviews aim at activating relevant prior knowledge and are supposed to provide a framework for the anchoring of new material. The notion was derived from Ausubel's 'advance organizing'. Highly similar types of overviews are Reigeluth's 'epitome' and the 'modeling' in the work by Collins, Brown and Newman.
- *Iterative cumulation* implies that knowledge of the core concepts of the material is accumulated by recurrently confronting the learner with those concepts, each time at a greater level of detail or sophistication. Iterative cumulation of knowledge is manifest in Bruner's 'spiral curriculum', Ausubel's 'progressive differentiation', Reigeluth's 'elaboration', White and Frederiksen's model progression and, in the work of Collins et al., though less directly, in the combination scaffolding and fading while using a global-to-local sequencing principle.

**SEQ** In SEQModel both iterative cumulation and advance overviewing are supported. SEQModel suggests imposing a hierarchical (generalization-specification) structure upon the target domain structure. This hierarchical structure is to act as a rationale for exploration at a coarse-grained level. At a fine-grained level, the original domain- and learning-related structures act as rationales. The top layer of the hierarchical structure is to be used as an advance organizer. As in the hierarchical structure used in the experiment described in chapter 6, the top layer introduces the central notions in the domain. The layout provided by SEQTool is then manipulated so that the learner will explore the domain in a general-to-specific direction. Descending a hierarchical structure in this way was argued to offer a form of iterative cumulation (section 3.4.1). That is, with each new level of detail provided, a link is established to the previous levels that subsume the present level.

**Lessons learned** A first question to ask was whether the meaningful layout invited to explore the experimental domain in a general-to-specific manner. One of the analyses of the exploratory patterns provoked by the meaningful layout was an analysis of perspective choice (section 6.4.3.4). This analysis of perspective choice revealed that the main difference between the layout condition and the other two conditions was that an evident hierarchical perspective choice was found in the layout condition only. It can thus be concluded that the meaningful layout in the experiment of chapter 6 indeed invited to explore in a way closely related to the pervasive hierarchical structure. What is more, from the analysis of direction preference, it was concluded that the subjects in the layout condition tended to explore the hierarchical structure in a general-to-specific direction. We may thus conclude that the meaningful layout indeed gave rise to a form of information space exploration that was argued to support iterative cumulation.

Whether this form of exploration positively affected the connection to prior knowledge could not be determined as such. The total of support provided by the meaningful layout was observed to lead to an enhanced acquisition of knowledge of structure, however, effects of the hierarchical perspective choice on acquisition of knowledge have not been assessed in isolation.

**MP** In MPModel, iterative cumulation is anticipated by the gradual evolution of model progression levels. In model progression, each next level is supposed to only introduce few new elements. Therefore, each model progression level essentially shows a large overlap with previous levels. By this, each next level is assumed to build upon the prior knowledge acquired from an exploration of the previous levels.

**Lessons learned** In the experiment reported in chapter 9, effects of model progression were assessed. One of the hypotheses in this experiment was that with a true accumulation of knowledge, misunderstanding in the first levels should have their effect on the understanding of later levels. In consequence, in the model progression condition the majority of misconceptions should be in the later levels, whereas in the control condition misconceptions might be distributed differently. However, this hypothesis was rejected since no differences were found between scores for subtests at the different levels.

## 10.3 Tailored rationales

A second requirement was that of 'tailored rationales'. In line with Posner and Strike, it was argued that sequence should be 'logically consistent' with the structure of the subject matter material. A first implication was that different types of structures require different types of rationales. In addition, different domains have different learning-related aspects. Hence, domain and learning-related features should be reflected in rationale choice.

A prescriptive model that implements a **tailored rationale** approach should make statements on which rationales to apply when, and in that, make statements on *categorical dominance*. In addition, such a model should be explicit on *how to handle combinations of rationales*. A second implication was that sequence should be closely related to the structures that were chosen to act as rationales. Hence, sequence should be **structure-related**.

### 10.3.1 Realization

The set of rationales suggested in the prescriptive theories reviewed in chapter 3 was limited in scope. When comparing this limited set with the set of rationales for sequencing content as mentioned by Posner and Strike (1976), the only conclusion could be that the majority of prescriptive theories ignore both characteristics of domains and aspects of the learning process.

The study of chapter 4 yielded an operationalization to the notion of tailored rationales. In this study we observed that with experienced authors rationale choice was certainly not restricted to a limited set of rationales. Hence, the single rationale approaches as described in chapter 3 could never have lead to sequences of a similar kind.

For the domains of validity, kinematics, biological taxonomy, and occupational groups we found a connection between domain and rationale choice. This observation provided support to the claim that rationale choice should be tailored to the domain.

Another observation was that sequence seemed to reveal a certain pattern. The pattern observed was named 'structure-relatedness'. Structure-relatedness implied connectivity, consistency of direction and, for some structure types, a 'natural' direction.

**SEQ** In SEQModel the notion of *tailored rationales* is implemented so that essentially each structure that can be detected (by SEQTool) is made to act as a rationale. However, within compound structures, compromises had to be made and as a consequence not all structures could actually be used as rationale for sequencing. The decision as to which structures to accept as rationales is based on notions of categorical dominance.

SEQTool supports *structure-related* exploration by implementing a technique for the 'meaningful' layout of graphical overviews as was proposed in chapter 3. Essentially, this meaningful layout is constructed using visualization templates that have been defined for two primitive structure forms. It was illustrated that these templates were likely to provoke connectivity and consistency of direction. Natural direction of exploration was to be achieved by manipulation of the orientation of the templates.

**Lessons learned** The experiment of chapter 6 showed that, for the experimental domain, the meaningful layout indeed enhanced structure-related exploration when compared to a randomly generated layout. This same experiment, however, provided no strong evidence for beneficial effects on the acquisition of knowledge of structure due to structure-related information space exploration. For propositional knowledge no effect was found due to structure-relatedness, for configural knowledge, structure-relatedness gave rise to only marginally better results.

**MP** MPModel currently suggests the application of two rationales, a simple-to-complex, and a perspective-based one. Support for a third rationale, a qualitative-quantitative one, could not be realized as the SMISLE lacked formalisms for qualitative modeling. A general purpose model prescribing two, maybe three rationales, could certainly not meet the requirement of tailored rationales. But, MPModel is very restricted in scope, it addresses domains that can be modeled by means of bond graphs only. Within this restriction, domains have many features in common. MPModel addresses the common features only and suggests rationales that refer to those features. It was, therefore, assumed that with a limited set of rationales still the main domain and learning-related aspects could be covered. By that, a model implementing a very limited set of rationales could still meet the requirement of *tailored rationales*.

MPModel does support *structure-related exploration* between MPLevels. Within an MPLevel, a learner is free to explore, but between levels the current implementation supports traversing to connected MPLevels only. Learners are free to return to previous levels, but are not allowed to 'jump' to entirely unrelated levels. Consistency of direction is achieved by guiding the learners to explore MPLevels in a fixed prescribed direction. That is, for simple-complex structures a natural simple to complex direction was prescribed, and learners were made to follow this direction.

It should be noted that in MPTool structure-relatedness is implemented as a directive form of support. The learner has freedom within a MPLevel but not between MPLevels.

**Lessons learned** In the experiment described in chapter 9 it was observed that the learners did not at all make use of the freedom provided at a local level. Although they were instructed to decide for themselves whether or not to make any of the assignments, the learners scrupulously attempted to make all available assignments. Apparently, they felt the need to be guided at a local level as well. Experiments in different domains by SMISLE partners in Kiel (de Jong *et al.*, 1995a) and Murcia (de Jong *et al.*, 1995b) suggest that learners benefit from guidance at a local level as provided by the assignments and not so much from the guidance provided at a global level as provided by MP. However, a follow up experiment with the SETCOM learning environment, as conducted by Swaak, van Joolingen, and de Jong (1996), has shown that if no guidance at a local level is available, a beneficial effect of MP on learning can become manifest.

## 10.4 Non-directive support

In chapter 2 it was argued that the presentation of material should be such that learners with different prior knowledge and learning styles should be able to adjust it to their own needs. Hence, the material should allow for flexibility. However, flexibility alone might not be an adequate solution, as flexibility is all too often accompanied by lack of support. Learners should be provided with the cognitive tools that could help them regulate their learning and to grasp the structure of the material. Such tools were to provide a form of *'non-directive'* support (see e.g., Njoo, 1994). This type of support is unobtrusive, that is, it does not force, rather it tacitly guides learners to explore in a beneficial a way.

The prescriptive work as reviewed in chapter 3 gave no indication as to how to design non-directive support. Hence, this question was addressed in this thesis. Several kinds of design constructs have been put forward. Below we will sketch these constructs, their manifestation in SEQTool and MPTool, and discuss lessons learned.

### 10.4.1 Realization

#### 10.4.1.1 Reducing the exploration space

A first form of non-directive support to be discussed here is that of 'reducing the exploration space'. The idea was to ease the students' regulation of information space exploration by providing them with a restricted set of options for exploration. This restriction should be realized by the hiding of suboptimal options.

**SEQ** 'Reducing the exploration space' was supported in SEQModel as well as in MPModel. In SEQModel the meaningful layout was set up to guide the students to remain connective. Each traverse should be to a directly connected topic, as non-connective traverses were assumed to be suboptimal. Thus, each time a learner would have to decide on a next topic to traverse to, the options were limited. Hence, with tacitly supporting connectivity, the exploration space had been extensively reduced.

**Lessons learned** A first observation from the experiment of chapter 6 was that the meaningful layout managed to provoke a highly connective form of exploration. Whether this connective exploration enhanced acquisition of knowledge of structure was assessed by means of correlational analysis only. In the meaningful layout condition, a modest correlation ($r = .35$, ns.) was observed between connectivity of exploration and gain of propositional knowledge. We may thus not conclude that the reduction of the exploration space by means of connectivity alone enhanced acquisition of knowledge of structure.

**MP** In MPModel the idea of exploration space reduction was applied as well. Model progression was perceived a potentially powerful method of providing learners with just enough freedom to let them be actively engaged in learning while not putting them at risk of getting lost. Such manageability of the environment was aimed at, by providing guidance at a global level, yet freedom at a local level. Locally, students have freedom to explore MPLevels. These levels are 'reduced' versions of the target model.

**Lessons learned** The series of experiments conducted in the SMISLE project (de Jong et al. (1995a; 1995a) and Swaak et al., (1996)) indicates that directive support at a local level (thus within MPLevels), as provided by the assignments, is more effective than directive support between levels only, as provided by model progression. The fact that learners chose to do most of the assignments, if not all, suggests that they were aware of the fact that they might benefit from additional guidance. This implies that a further reduction of the exploration space than was offered by MP might be desirable.

#### 10.4.1.2 Well designed graphical overviews

A second potentially powerful form of non-directive support was that of providing an additional (well designed) graphical overview of the subject matter structure. The idea was that such an overview would provide a map of the domain and by that make it easier to plan and monitor the exploratory trajectory.

Providing well designed graphical overviews as an add-on to a learning environment was thought to give rise to a 'dual mode' effect. This term refers to the effect obtained from delivery of one and the same message concurrently by means of various media. Visualization is assumed to be a powerful means in its own right of conveying meaning. Diagrams 'exploit the human visual skill', as Nardi and Craig (1993) remark. Visualization is thought to take advantage of the ability to perceive spatial relationships and to infer structure and meaning from those relationships.

The question is whether adding a visual overview to a hypertext system may contribute substantially to the acquisition of the information that was otherwise acquired without the support of such overview. De Vries (1994) discusses the question whether pictures enhance text understanding. She concludes lack of theory on this subject, but sees two prevailing hypotheses emerging from the literature. A first one is the 'integrated dual-code' hypothesis (Mayer & Anderson, 1991). This hypothesis assumes that with concurrent presentation of text and pictures not only representational connections are created between textual-textual en pictorial-pictorial representation but also that connections are created between textual and pictorial material. Indeed, benefits of a concurrent presentation of textual and pictorial material compared to single code presentations were found in the context of a problem transfer task (see Mayer & Anderson, 1991). A second hypothesis is the 'mental model' hypothesis as put forward by Glenberg and Langston (Glenberg & Langston, 1992, in de Vries, 1994), this hypothesis assumes that concurrent presentation of text and pictures assists in the construction of richer mental models than would result from the presentation of either of them. All in all, both hypotheses assume benefits of a combination of pictures and text.

**SEQ** SEQTool facilitates the generation of a meaningful layout visualization of the structure the subject matter. This visualization was designed to support structure-related exploration as well as it was assumed to directly convey information of the structure of the subject matter.

**Lessons learned** One of the questions of the SEQ experiment in chapter 6 addressed the direct effects of meaningful layout visualization. To answer this question, direct effects of a meaningful layout were to be assessed isolated from indirect effects due to enhanced exploratory behavior. To this end, two graphical overviews were created, one constructed according to the in chapter 5 sketched principles for layout (the meaningful layout condition), a second according to a randomized positioning (the structure-related condition) where structure-related exploration was supported by hints. In a comparison of the results of these two conditions, any differences should be due to the nature of the visualization. All this under the assumption that the nature of information space exploration within the structure-related condition and that within the layout condition did not differ fundamentally.

The experiment in chapter 6 did reveal an effect due to the nature of visualization. The meaningful layout resulted in a significantly higher gain of knowledge of structure. Under the above mentioned assumption, it could be perceived to be a direct effect of the meaningful layout visualization.

#### 10.4.1.3 Deliberate use of conventions

Behavior is strongly guided by conventions. Conventions can thus be used to guide behavior. One of the potentially powerful ideas for the design of non-directive support is that of deliberate use of conventions for guiding behavior.

**SEQ** Deliberate use of conventions was one of the forms of non-directive guidance as applied within the SEQ environment. Here a convention related to reading direction was applied to guide learners to explore a structure in a structure-related manner. People from western cultures will generally read from left-to-right (see e.g. Levelt, 1982) and it was found that this learned behavior goes beyond the reading of text. A predominant left-to-right direction was also found in exploration of graphical overviews (see chapter 5).

In SEQTool, this reading convention was used to decide upon the layout of a graphical overview. The resulting layout should be such that learners, when exploring in a 'reading direction', would explore in a beneficial manner.

**Lessons learned** SEQTool's implementation of support based on the deliberate use of conventions is limited. SEQTool can handle primitive structures and very limited nested structures. In the structure used in the experiment of chapter 6 SEQTool's orientation rules were applied to display the templates for the hierarchical and the first temporal structure. The analysis of exploratory patterns revealed that for these two structures, the support indeed gave rise to the expected reading direction. By that, the hierarchical structure was explored in a general-to-specific order and the temporal structure in a chronological order.

## 10.5 Reflections on methodology

**An interdisciplinary endeavor** The work reported in this thesis has been highly interdisciplinary of nature. Learning psychology was the source of requirements for support. Instructional design theory provided some of the design constructs. Complementary design constructs resulted from a bottom up study on the way experienced authors organized material. If this study fitted any discipline, it should be the discipline of knowledge engineering. Then, techniques from information technology helped to operationalize the design constructs and prescriptions. Finally, with the experimental work dedicated to an assessment of the merits of the proposed support, we were back to learning psychology.

It was only for the achievements of the various disciplines mentioned above that the exercises reported in this thesis could be brought to an end. When designing support, one would naturally turn to the discipline of instructional design theory. However, this discipline could only very partially provide principles and design constructs that satisfied all requirements. On the other hand, techniques from knowledge engineering and information technology turned out to be highly instrumental.

**A knowledge engineering approach to theory development** With respect to the contribution from the discipline of knowledge engineering, one of the surprises of this study was the wealth of information on instructional design that could be extracted from instructional material. Printed instructional material was found to readily reveal its rationales. In addition, it revealed categorical dominance of the various rationales used, as well as patterns in sequencing.

The field of instructional design theory lacks systematic methods for theory development. Theory development has largely been a creative process that was usually only indirectly based on ideas on how experienced teachers organized subject matter material. It is our impression that the discipline of instructional design could gain a lot from using knowledge engineering techniques for theory development.

A frequently heard criticism on instructional design theory is that it prescribes methods that are entirely different from the methods a teacher or author would employ naturally. Instructional design theories are frequently judged too 'theoretical', too remote from the practice of instructional design. For instance, constructing a prerequisite hierarchy is an awesome job, and the gain from it is not always evident.

Theory based on knowledge engineering techniques is likely to be closer related to the practice of instructional design. Knowledge engineering implies generalizing from the instructional design by experienced authors. In consequence, the resulting instructional design theory is likely to be less 'theoretical'.

One remark still should be made regarding the knowledge engineering approach adopted in the present study. When designing theory for the support of exploratory learning, ideally one should extract expertise from experts in the design of environments for exploratory learning. However, by lack of long time experts in this area, we had to do with the expertise of those working in the field of expository instruction. The question now rose whether prescriptions and design constructs derived from expository material could be useful to the design for exploratory learning. The impression from this work is that they are. The prescriptions that together form the model of structure-related sequencing turned out to be readily applicable to the design of support for a hypertext environment for exploratory learning. Similarly, prescriptions on sequencing subject matter on oscillation that were derived from expository material were found to be readily applicable to the design of simulation-based environments for exploratory learning.

In the present study, it turned out that prescriptions derived from expository material could to a large extent be applied in the design of environments for exploratory learning. More generally, it is not unlikely that for the development of advanced learning technology much of the theory dedicated to or derived from traditional technology still can be used.

**An information technology approach for operationalization and testing** Above we mentioned the critique regarding current instructional design theory being too 'theoretical'. A second type of critique on prescriptive theory related to the vagueness of its prescriptions. Many of the prescriptive theories reviewed were so-called first generation instructional design theories. First generation theory is relatively coarse-grained in nature. Such a theory provides a small number of rather general principles that are geared towards use by human instructional designers. Still, much of the discussion on the merits of the various theories could be traced back to differences in interpretation by the human instructional designers.

The intention of this work was to design theory for computer based support. We aimed to provide authors with both technical and conceptual support tailored to their domain. Yet, an important side effect was that, to enable implementation, we had to develop theory that was non-ambiguous. The relatively vague first generation theory was certainly not suitable for a ready implementation. In theory suitable to computer based design, prescriptions could only refer to generic aspects of domains that were made explicit in the system. Hence, the step toward computerized support for design forced to be explicit on the exact meaning of the prescriptions. Thus, the use of information technology in instructional design had as side effect that theory had to be formulated in a highly precise manner.

The development of theory for computer based support for design also has a second side effect. Design theory could and should be finer grained. The notion of tailored rationales implied that sequence should be closely related to the target structures. By being coarse-grained in nature, first generation theory just did not allow this. In theory-based authoring systems, prescriptions had to be operationalized to suit different types of domain structure. Operationalization thus required finer grained second generation theory.

A final effect to be discussed here is that implementation of design theory in an authoring system substantially facilitates the validation of that theory. Authoring systems are great tools for the systematic assessment of the merits of particular design constructs. In the SMISLE project, the availability of tools for the construction of assignments and model progression made it possible to assess the effects of those measures in a variety of domains. In SMISLE, experiments were done in three different domains. Different authors implemented different domains, yet little confusion on the exact interpretation of the nature of instructional support was observed. The availability of an authoring tool is thus of great help as it facilitates a correct interpretation of the instructional design prescriptions.

All in all, the trend to provide support for instructional design in the form of theory-based authoring tools might give a strong push to the development of instructional design theory. Implementation requires theory that leaves no room for discussion on interpretation, it allows the use of fine-grained, multi rationale theory and it provides a test-bed for the assessment of the merits of the theory.

**New methods and instruments** As research methodology is instrumental to learning psychology, the disciplines of knowledge engineering and information technology can be instrumental to the development of instructional design theory. It was argued here that the application of knowledge engineering techniques might very well lead to design theory that was likely to be closer to the design practice. The application of information technology techniques might help to operationalize that theory. As a result, theory might leave less room for debate on interpretation, be more tailored to the variety of domains to be covered, and finally its validity might be more readily assessed. This thesis thus ends with advocating the application of methods from knowledge engineering and information technology to provide authors and learners with the tools they would really like to use.

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# Material used in chapter 4 A

## A.1 Overview of the order of presentation of similar subject matter material, chapter 4

### A.1.1 Validity

Figure A.1 provides a reconstruction of the original domain structures from four texts on the subject of 'validity' in material on statistics or methodology for the social sciences by respectively (Allen & Yen, 1979; Meerling, 1984; Kidder, 1985; Crocker & Algina, 1986)

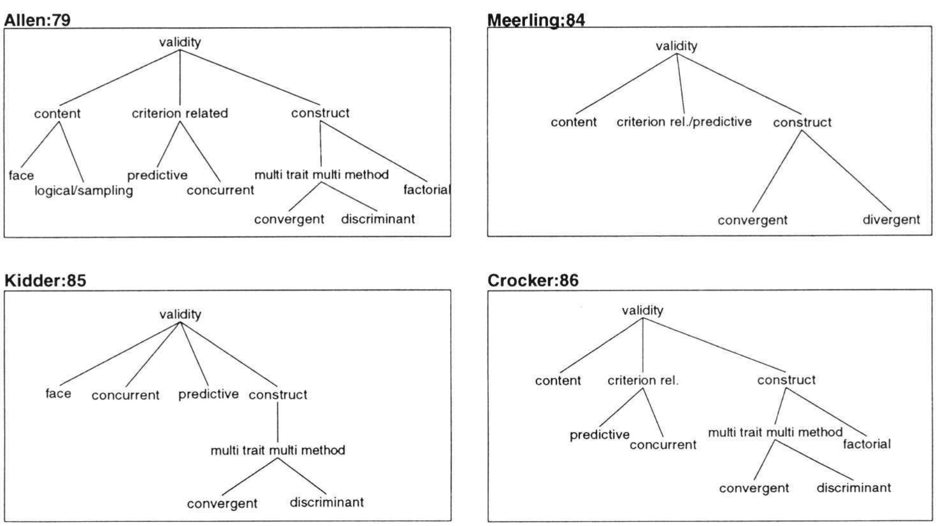



Figure A.1: Reconstructions of the domain structures of four texts on validity

Below, an overview can be found of the order of presentation of topics of the above mentioned sources on validity.

### A.1.2 Kinematics

Figure A.3 provides a reconstruction of the original domain structures from four texts on the subject of kinematics in material on physics by respectively (Vakbegeleidingsgroep Natuurkunde., 1982; Middelink, 1978; Middelink, 1979; Schweers & van Vianen, 1970; Alonso & Finn, 1978)

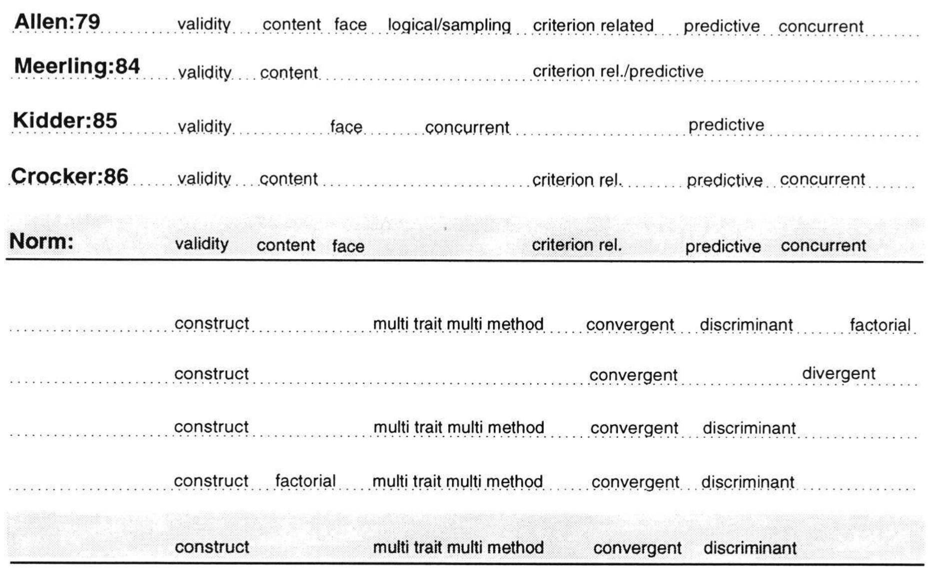



Figure A.2: Presentation of material on the subject of 'validity'

Below, an overview can be found of the order of presentation of topics of the above mentioned sources on kinematics.

### A.1.3 Biological classification

Figure A.5 provides a reconstruction of the original domain structures from four texts on the subject of biological classification by respectively (Kreutzer & Oskamp, 1975; Schraer & Stoltze, 1991; Baker *et al.*, 1991; Biggs et al., 1991). The left and middle branch of the domain reconstruction of Biggs lack a label at the middle level. However, at this level a discussion is provided of the groups of organisms, so a source of a branch was depicted.

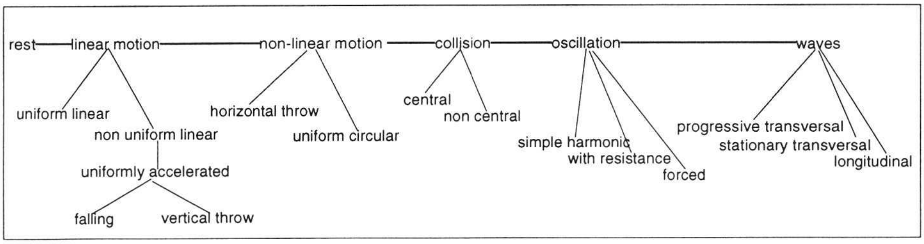
Below, an overview is provided of the order of presentation of topics of the above mentioned sources on biological classification.

### A.1.4 Occupational groups

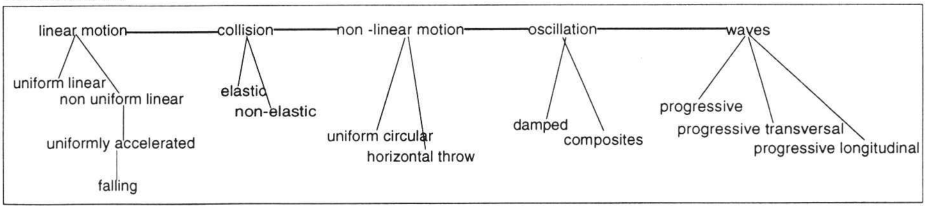
Figure A.7 provides a reconstruction of the original domain structures from four texts on the subject of occupational groups in material on geography by respectively (Van Dongen *et al.*, 1983; de Boer *et al.*, 1983; Allessie & van Mierlo, 1969; Zuelen *et al.*, 1985)

Below, an overview is provided of the order of presentation of topics of the above mentioned sources on occupational groups.

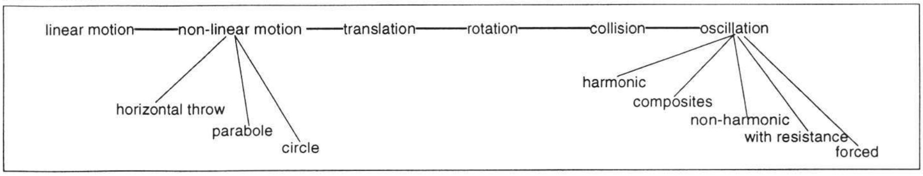
**Middelink:78/79**




**Schweers:70**




**Alonso:78**




**Nelkon:70**

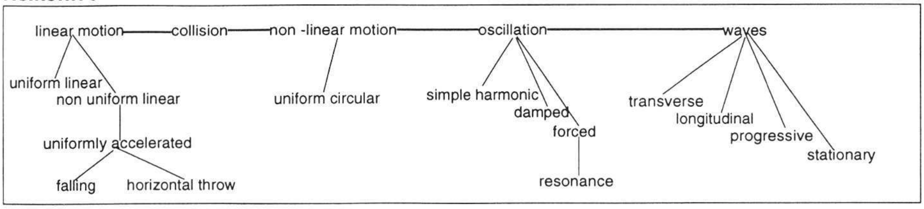



Figure A.3: Reconstructions of the domain structures of four texts on kinematics

| Text | Part 1 | Part 2 | Part 3 | Part 4 |
|---|---|---|---|---|
| **Middelink:78/79** | rest, linear motion, uniform linear, non uniform linear, uniformly accelerated | falling, vertical throw, non-linear motion, horizontal throw, uniform circular, collision, central | non central, oscillation, simple harmonic, with resistance | forced, waves, progr. transversal, stationary transversal, longitudinal |
| **Schweers:70** | linear motion, uniform linear, non uniform linear, uniformly accelerated | falling, collision, elastic | non-elastic, non -linear motion, uniform circular, *horizontal throw**, oscillation, damped | composites, waves, progr., progr. transversal, progressive longitudinal |
| **Alonso:78** | linear motion | non-linear motion, horizontal throw, parabole, circular, translation, rotation, collision | oscillation, harmonic, comp. n-harm., with resistance | forced |
| **Nelkon:70** | linear motion, uniform linear, non uniform linear, uniformly accelerated | falling, horizontal throw, collision | non -linear motion, uniform circular, oscillation, simple harmonic, damped | forced, resonance, waves, transverse, longitudinal, progressive, stationary |
| **Norm** | linear motion, uniform linear, non uniform linear, uniformly accelerated | falling, non-linear motion**, horizontal throw, uniform circular**, collision | non-linear motion**, uniform circular**, oscillation, harmonic, damped | forced, waves, transverse, longitudinal |

**: Elements marked with a * deviate from the norm sequence*

***: The elements marked with ** are found twice in the norm pattern. Evidently two logical patterns emerged, one where linear and non- linear motion were treated succesively, one where linear motion was followed by collision, and non- linear motion was only treated afterwards. It would not be just to judge one of the two patterns as optimal. Hence, both patterns are accepted as valid (forward) sequences.*

Figure A.4: Presentation of four texts on the subject of kinematics

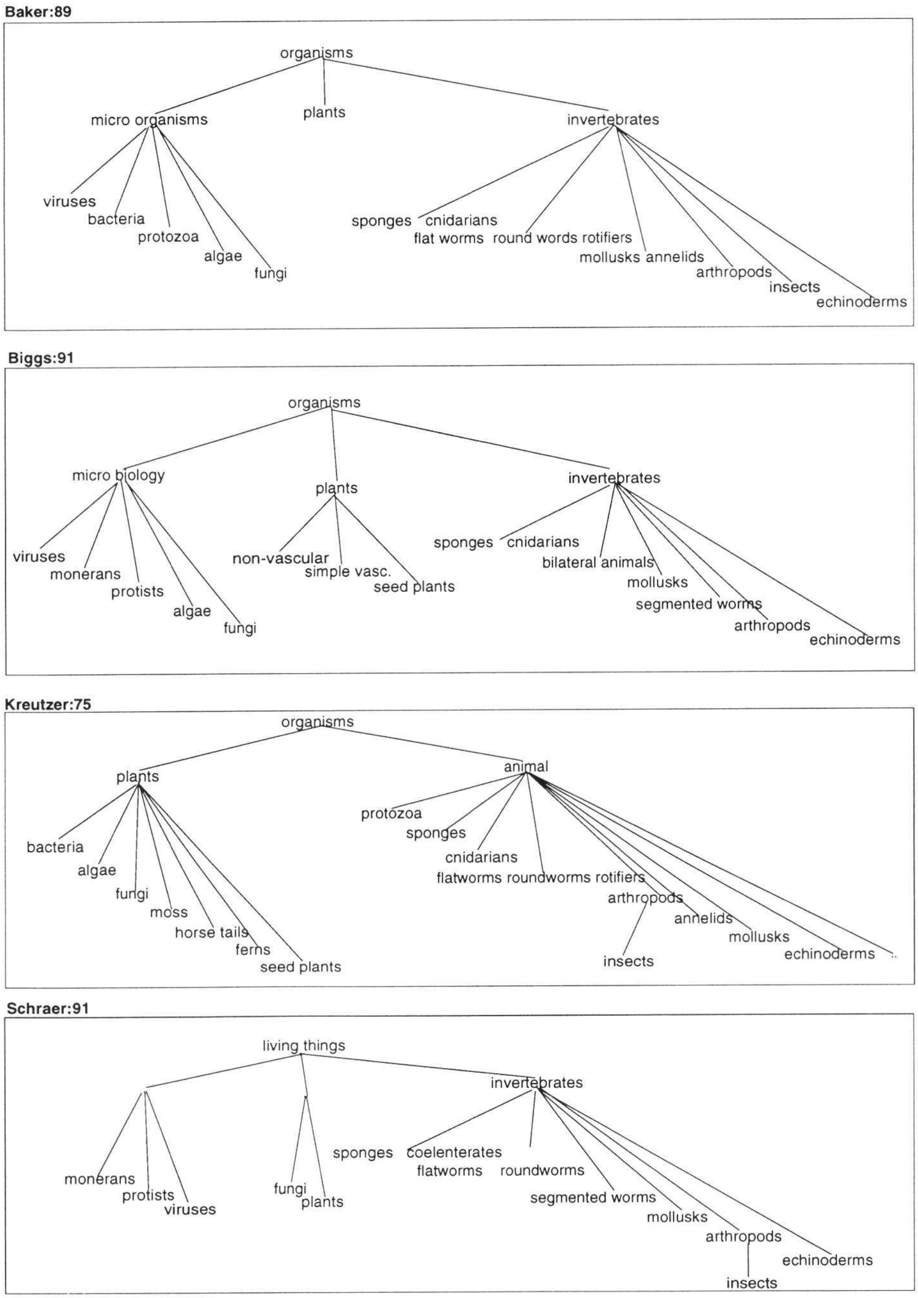



Figure A.5: Reconstructions of the domain structures of four texts on biological classification

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Baker:89** | viruses | | bacteria | protozoa | algae | fungi | plants | | |
| **Biggs:91** | viruses | monerans | | protozoa | algae | fungi | non-vascular | simple-vasc. | |
| **Kreutzer:75** | | | bacteria | | algae | fungi | moss | horsetails | ferns |
| **Schraer:91** | | monerans | | protists | *viruses** | fungi | plants | | |
| **Norm:** | viruses | monerans | bacteria | protozoa | algae | fungi | plants | | |

| | | | | | |
|---|---|---|---|---|---|
| | | sponges | cnidarians | flatworms | roundworms |
| seed plants | | sponges | cnidarians | bilateral annimals | |
| seed plants | *protozoa** | sponges | cnidarians | flatworms | roundworms |
| | | sponges | coelenterates | flatworms | roundworms |
| seed plants | | sponges | cnidarians | flatworms | roundworms |

| | | | | | | |
|---|---|---|---|---|---|---|
| rotifiers | mollusks | annelids | arthropods | insects | | echinoderms |
| segm. worms | mollusks | | arthropods | | | echinoderms |
| rotifiers | | annelids | arthropods | insects | *molluks** | echinoderms |
| segm. worms | mollusks | | arthropods | insects | | echinoderms |
| | mollusks | annelids | arthropods | insects | | echinoderms |

**: Elements marked with a * deviate from the norm sequence*

Figure A.6: Presentation of four texts on the subject of biological classification

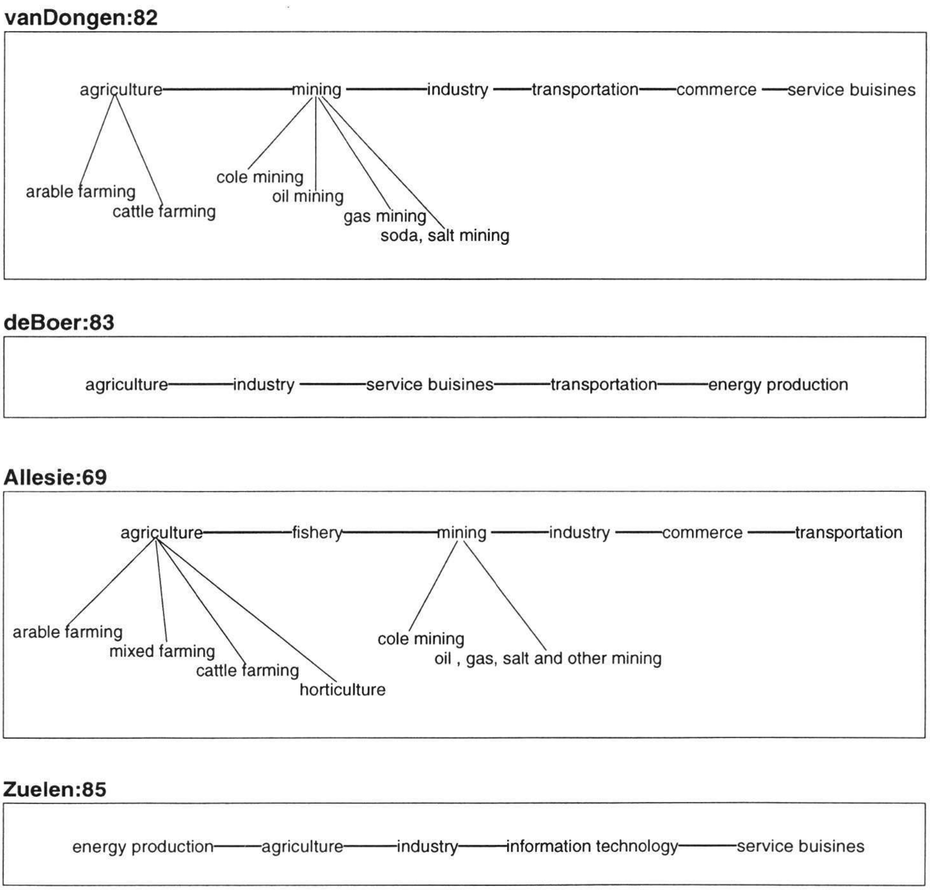



Figure A.7: Reconstructions of the domain structures of four texts on occupational groups

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **vanDongen:82** | | agriculture | | mining | industry | | |
| **deBoer:83** | | agriculture | | | industry | | |
| **Allesie:69** | | agriculture | fishery | mining | industry | | commerce |
| **Zuelen:85** | *energy production** | agriculture | | | industry | inf. tech. | |
| **Norm:** | | agriculture | | mining | industry | | |

| | | | | |
|---|---|---|---|---|
| | | transportation | commerce | *service buisines** |
| | service buisines | transportation | energy production | |
| | | transportation | energy production | |
| | service buisines | | | |
| | service buisines | transportation | energy production | |

**: Elements marked with a * deviate from the norm sequence*

Figure A.8: Presentation of four texts on the subject of occupational groups

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# MPModel

# B

This appendix contains 1) a declaration of the vocabulary that is used to make statements on model progression and 2) a definition of the dimensions that act as rationale in the MPAproach. The appendix is part of chapter 7.

## Declaration

Let Mx be the model of x:

$$M_x = \langle MS_x, MB_x \rangle$$

Let $MS_x$ be the structural model of x

$$MS_x = \langle N_x, J_x \rangle$$

where the set of n-ports is defined as:

$$N_x = \{NP_i, \ldots, NP_n\}$$

and $NP_i$ is either:

$$\begin{array}{rcll} NP_i & = & \text{inertia} & or, \\ NP_i & = & \text{capacitor} & or, \\ NP_i & = & \text{resistor} & or, \\ NP_i & = & \text{effort source} & or, \\ NP_i & = & \text{flow source} & or, \\ NP_i & = & \text{transformer} & or, \\ NP_i & = & \text{gyrator} & or, \\ and \quad N_x & \neq & \emptyset & \end{array}$$

where the set of junctions is defined as:

$$Jx = \{JU_i, \ldots, JU_n\}$$

and $JU_i$ is either

$$\begin{array}{rcll} JU_i & = & \text{0-junction} & or, \\ JU_i & = & \text{1-junction} & \end{array}$$

Let $MB_x$ be the behavioral model of x:

$$MB_x = \langle V_x, REL_x \rangle$$

where the set of variables is defined as:

$$V_x = \{V_x^{input}, V_x^{state-output}\}$$

where the combined set of state and output variables is defined as:

$$V_x^{state-output} = \{Vset_x^{flow}, Vset_x^{effort}, Vset_x^{energy}\}$$

where the set of flow variables is defined as:

$$Vset_x^{flow} = \{V_x^{displacement}, V_x^{flow}\}$$

where the set of effort variables is defined as:

$$Vset_x^{effort} = \{V_x^{momentum}, V_x^{effort}\}$$

where the set of energy variables is defined as:

$$Vset_x^{energy} = \{V_x^{kinetic}, V_x^{potential}\}$$

## Simple-complex dimension

Simple-to-complex progression is defined as follows:

let

$$MS_x = \{N_x, J_x\} \wedge MS_y = \{N_y, J_y\}$$

then

$$N_x \subset N_y \wedge N_y - N_x \neq \emptyset \Leftrightarrow \text{simple-to-complex}(MS_x, MS_y)$$

## Perspective dimension

An effort perspective is defined as follows:

$$\exists i V_i = V^{momentum} \wedge \exists j V_j = V^{effort} \Rightarrow \text{Perspective} = P^{Effort}$$

A flow perspective is defined as follows:

$$\exists k V_k = V^{displacement} \wedge \exists l V_l = V^{flow} \Rightarrow \text{Perspective} = P^{flow}$$

An energy perspective is defined as follows:

$$\exists m V_m = V^{kinetic} \wedge \exists n V_n = V^{potential} \Rightarrow \text{Perspective} = P^{energy}$$

Thus the set of possible perspectives is:

$$Pset = \{P^{effort}, P^{flow}, P^{energy}\}$$

### Derivation-based view dimension

A momentum view is defined as follows:

$$\exists i V_i = V^{momentum} \Rightarrow View^{db} = View^{momentum}$$

An effort view is defined as follows:

$$\exists j V_j = V^{effort} \Rightarrow View^{db} = View^{effort}$$

A displacement view is defined as follows:

$$\exists k V_k = V^{displacement} \Rightarrow View^{db} = View^{displacement}$$

A flow view is defined as follows:

$$\exists l V_l = V^{flow} \Rightarrow View^{db} = View^{flow}$$

Thus the set of possible derivation-based views are:

$$View^{db-set} = \{View^{momentum}, View^{effort}, \\ View^{displacement}, View^{flow}\}$$