

# Contents

<b>Contents</b> .....	<b>i</b>
<b>List of Figures</b> .....	<b>vii</b>
<b>List of Tables</b> .....	<b>x</b>
<b>List of Listings</b> .....	<b>xi</b>
<b>Acknowledgments</b> .....	<b>xii</b>
<b>Declarations</b> .....	<b>xiii</b>
<b>Abstract</b> .....	<b>xiv</b>
<b>Abbreviations</b> .....	<b>xv</b>
<b>1 Introduction</b> .....	<b>1</b>
1.1 Construction of computer models by children .....	3
1.2 Construction of computer models by adults .....	5
1.3 Introducing Empirical Modelling .....	6
1.4 Motivations for the thesis .....	7
1.5 Research contributions .....	12
1.6 Contents of the thesis .....	14
<b>2 Paradigms for exploratory modelling</b> .....	<b>18</b>
2.0 Overview of the chapter .....	18
2.1 Empirical Modelling and Spreadsheets: In principle and practice .....	18
2.2 Spreadsheets .....	20
2.2.1 Introducing spreadsheets .....	20

2.2.2	Key aspects of exploratory modelling .....	25
2.2.3	Spreadsheets for exploratory modelling .....	29
2.3	Extensions of the spreadsheet concept .....	31
2.3.1	Forms/3 .....	31
2.3.2	Spreadsheets for Images .....	34
2.3.3	Agentsheets .....	36
	An Agentsheets example .....	37
	Agentsheets and the key aspects of exploratory modelling ..	40
2.4	Practical Empirical Modelling .....	43
2.4.1	Definitive scripts .....	44
2.4.2	The TkEden modelling tool .....	45
2.4.3	State-transitions: Implementing agency in TkEden .....	50
2.4.4	Building an example model .....	51
2.4.5	Distributed modelling: The DTKEden tool .....	53
2.4.6	Empirical Modelling for exploratory modelling .....	55
2.5	Empirical Modelling and spreadsheets.....	57
2.6	Summary of the chapter .....	62
<b>3</b>	<b>A computational perspective on computers and learning .....</b>	<b>63</b>
3.0	Overview of the chapter .....	63
3.1	Challenges for computers for learning .....	63
3.2	A perspective on learning .....	67
3.2.1	Learning skills, learning about artefacts and learning about situations .....	69

3.2.2	An experiential framework for learning (EFL) .....	73
3.3	Learning by experience .....	77
3.3.1	Experiential learning .....	78
3.3.2	Radical Empiricism .....	80
3.4	Principles of Empirical Modelling .....	82
3.4.1	Construals .....	83
3.4.2	State-as-experience and behaviour-as-abstracted .....	85
3.4.3	Observation, dependency and agency .....	88
3.5	Modelling restaurant management .....	93
3.5.1	Experiential learning and the restaurant manager model .....	96
3.5.2	Empirical Modelling principles and the restaurant manager model .....	96
3.6	Chapter Summary: Empirical Modelling and the EFL .....	99
<b>4</b>	<b>An educational perspective on computers for learning .....</b>	<b>102</b>
4.0	Overview of the Chapter .....	102
4.1	Constructionism and instructionism .....	102
4.1.1	Objectivism, Cognitivism and Constructivism .....	103
4.1.2	Instructionism and Constructionism .....	105
4.2	Bricolage .....	109
4.3	Situated Learning .....	116
4.4	Concept Maps .....	119

4.4.1	Reviewing concept maps .....	119
4.4.2	Concept Maps and the EFL .....	122
4.5	Programming for domain learning .....	124
4.5.1	Programming from a learning perspective .....	124
4.5.2	Conventional programming, constructionism and the EFL ...	128
4.6	Empirical Modelling, constructionism and the EFL .....	130
4.6.1	Empirical Modelling and bricolage .....	131
4.6.2	Empirical Modelling and situated learning .....	134
4.7	The digital watch case study .....	136
4.8	Summary of the chapter .....	143
<b>5</b>	<b>Scaffolding different types of learning .....</b>	<b>144</b>
5.0	Overview of the chapter .....	144
5.1	Model use vs Model building .....	144
5.1.1	Constructionist learning environments .....	144
5.1.2	Supporting different types of learning .....	148
5.2	Learning as comprehension of a fixed referent .....	151
5.2.1	The racing cars case study .....	152
5.3	Learning as exploring possibilities and invention .....	158
5.3.1	Cognitive layering .....	158
5.3.2	The noughts-and-crosses case study .....	160
5.3.3	Case study - Adapting layers to form a family of models .....	164
V1	- Altering the computer strategy .....	166

	V2 - Altering the rules of the game .....	169
	V3 - Altering the pieces that are being played .....	171
	V4 - Altering the board .....	173
	5.4 Learning languages .....	174
	5.4.1 The Agent-Oriented parser .....	175
	5.4.2 Case study - A clown-and-maze language .....	177
	5.4.3 Case study - A learning environment for relational query languages .....	181
	5.5 Chapter Summary: Scaffolding with Empirical Modelling .....	189
<b>6</b>	<b>Exploratory learning and the EFL .....</b>	<b>192</b>
	6.0 Overview of the chapter .....	192
	6.1 Integrating model used and model building .....	192
	6.2 Monotone Boolean Functions in 4 variables .....	195
	6.2.1 P4: The lattice of subsets of {1,2,3,4} ordered by inclusion ...	198
	6.2.2 FDL4 as the lattice of decreasing subsets of P4 ordered by inclusion.....	200
	6.2.3 FDL4 as monotone boolean functions in 4 variables ordered by implication .....	202
	6.2.4 S4: The symmetric group on 4 symbols .....	204
	6.3 The Heapsort model .....	207
	6.4 The Robotic Simulation Environment .....	212
	6.4.1 Building and programming robots .....	214
	6.4.2 The Empirical Modelling Robotic Simulation Environment ..	219

6.4.3 Layering in the Robotic Simulation Environment .....	221
6.5 Chapter summary: Supporting learning across the EFL in Empirical Modelling .....	226
<b>7 Summary and conclusions .....</b>	<b>228</b>
7.0 Overview of the chapter .....	228
7.1 Review of the thesis .....	228
7.2 Future work .....	231
7.2.1 Empirical Testing .....	231
7.2.2 Comparative studies .....	232
7.2.3 Developing an Empirical Modelling environment for children .....	232
7.3 Conclusions .....	234
7.3.1 Reservations about the research .....	234
7.3.2 Conclusions of the thesis .....	235
<b>Bibliography .....</b>	<b>237</b>
<b>Appendix A - An example of constructing a model for the simple game of Jugs .....</b>	<b>257</b>
<b>Appendix B - An example of building a parser .....</b>	<b>267</b>
<b>Appendix C - Glossary of models used in the thesis .....</b>	<b>280</b>
<b>Appendix D - Example model building interactions in EM .....</b>	<b>286</b>

## List of Figures

Figure 2.1: Connecting Empirical Modelling, practical spreadsheet tools and principles of spreadsheet use .....	20
Figure 2.2: Cyclic dependency .....	22
Figure 2.3: An example spreadsheet and chart in Excel .....	23
Figure 2.4: A diagram of an Excel spreadsheet with the key characteristics of the paradigm being highlighted .....	24
Figure 2.5: Cantwell-Smith's program, process and subject matter .....	25
Figure 2.6: A simple tax spreadsheet .....	26
Figure 2.7: A spreadsheet to explore income tax .....	27
Figure 2.8: Example of a Forms/3 form with a set of cells to define a circle and its attributes .....	33
Figure 2.9: An example of a spreadsheet for images, taken from [Lev94] .....	35
Figure 2.10: Structure of an Agentsheet, taken from [Rep93] .....	37
Figure 2.11: A screenshot of the Agentsheets epidemic model .....	38
Figure 2.12: A VisualAgenTalk rule for a person in the epidemic model .....	39
Figure 2.13: The significant concepts associated with Empirical Modelling .....	43
Figure 2.14: The three windows in the TkEden modelling environment .....	46
Figure 2.15: An example Donald fragment to define a circle .....	47
Figure 2.16: An example Scout fragment to display the drawing in Figure 2.16 in a window .....	48
Figure 2.17: An example of a Sasami fragment to display a coloured cube .....	49
Figure 2.18: The Jugs model from Appendix A .....	52
Figure 2.19: Screenshots of the Clayton Tunnel simulation from the perspectives of each of the participants .....	54
Figure 2.20: A small example TkEden spreadsheet .....	58
Figure 2.21: The TkEden spreadsheet illustrating geometrical shapes in a spreadsheet .....	60

Figure 2.22: The restaurant model in a spreadsheet .....	61
Figure 3.1: An experiential framework for learning .....	74
Figure 3.2: Kolb's experiential learning cycle .....	78
Figure 3.3: State-based and Behavioural-based views on development processes ..	87
Figure 3.4: The restaurant manager model .....	94
Figure 4.1: Relating constructionism and instructionism to the EFL .....	108
Figure 4.2: An example concept map of this chapter .....	120
Figure 4.3: The simple jugs model from Figure 2.19 in the DMT .....	123
Figure 4.4: The development history of the digital watch .....	138
Figure 4.5 - The digital watch artefact (top right), an analogue clock (middle right) and a mental stategraph (left) .....	139
Figure 4.6: Situational observables - timing two runners .....	142
Figure 4.7: A partially obscured digital display .....	142
Figure 5.1: A spectrum of learning perspectives .....	147
Figure 5.2: Soloway's TILT model [SGH94] .....	150
Figure 5.3: The microworlds in the racing cars model .....	153
Figure 5.4: Microworld 2 of the racing cars model .....	154
Figure 5.5: Microworld 3 of the racing cars model .....	155
Figure 5.6: Microworld 4 of the racing cars model .....	156
Figure 5.7: Microworld 7 of the racing cars model .....	157
Figure 5.8: Differences between scaffolding and cognitive layering .....	159
Figure 5.9: The structure of the OXO model .....	161
Figure 5.10: Microworld 1 of the OXO model .....	162
Figure 5.11: Microworld 2 of the OXO model .....	163
Figure 5.12: Microworld 4 of the OXO model .....	164
Figure 5.13: A tree of possible models based on the cognitively layered OXO model .....	165
Figure 5.14: A problem situation for the OXO computer player .....	167

Figure 5.15: The board and pieces of the number cross model .....	171
Figure 5.16: The game of number cross with the rules present .....	172
Figure 5.17: Adaptable and formal languages .....	175
Figure 5.18: The structure of the clown-and-maze language .....	178
Figure 5.19: The clown and maze environment .....	179
Figure 5.20: The relationship between the query languages in SQL-EDDI .....	182
Figure 5.21: Example queries in SQL and EDDI to illustrate the flaws in SQL .....	185
Figure 5.22: The SQL-EDDI environment in use, illustrating queries 2a) and 2b) ..	185
Figure 5.23: Using the RAT to support understanding of operations on tables .....	188
Figure 6.1: Conflating model-building and model-use .....	194
Figure 6.2: The diverse components of the MBF4 model .....	196
Figure 6.3: (a) The lattice of subsets P4; (b) an example of a decreasing subset of P4 .....	199
Figure 6.4: The Hasse diagram with 166 nodes corresponding to the set of decreasing subsets of {1,2,3,4} .....	200
Figure 6.5: (a) A Cayley diagram for S4; (b) an example of a CPL map .....	204
Figure 6.6: The complete MBF4 model .....	206
Figure 6.7: The heapsort model showing a representation of a heap .....	209
Figure 6.8: Heapsort and its associated formal specification .....	212
Figure 6.9: An example robot and its main features .....	215
Figure 6.10: Using the IPPE to create a command .....	216
Figure 6.11: The iterative robot programming cycle .....	217
Figure 6.12: Learning and the Robotic Simulation Environment .....	220
Figure 6.13: The RSE being used to investigate the relationship between the motors and the robot's movement.....	222
Figure 6.14: An example task for a robot program to solve (from [JKS02]) .....	224
Figure 6.15: The RSE in use in solving the task from Figure 6.14 .....	225
Figure A.1: The simple jugs model .....	266

## List of Tables

Table 2.1: Some example Forms/3 commands, from Appendix B of [BAD <sup>+</sup> 01] .....	32
Table 4.1: Differences between bricolage and ‘planning’, as identified in [TP91, Ben01] .....	115
Table 4.2: Comparing problem solving in situation and abstract settings (adapted from Table 1 in [BCD89]) .....	117
Table 4.3: Comparing school learning and everyday learning [Res87] .....	118
Table 5.1: The evaluation strategy for player X in OXO .....	166

## List of Listings

Listing 2.1: An example of a simple definitive script .....	44
Listing 3.1: Part of an LSD specification for the restaurant manager model .....	98
Listing 5.1: The new definition that describes the state of the board for when player x should play .....	169
Listing 5.2: The example command for the down operator in the krusty language described in section 5.4.2 .....	176
Listing 5.3: An EDDI extract illustrating the definition of the FRUITS database ...	183
Listing 6.1: An example robot program listing .....	216

## **Acknowledgements**

I am indebted to a number of people who have helped me in various ways during the writing of this thesis.

First and foremost, I would like to thank my supervisor and friend Meurig Beynon for his unselfish support throughout the preparation of this thesis. I am very grateful for all the comments, discussions, encouragement and feedback. This thesis would not have been completed without his assistance.

Thanks also to the other members of the Empirical Modelling research group for providing a stimulating and interesting environment within which to conduct research. In particular, thanks to Steve Russ for useful guidance whenever it was requested, and a huge thank you to Ashley Ward for his friendship, discussions and seemingly unbounded technical knowledge. Further thanks to Dave Pratt from Warwick Institute of Education for stimulating discussions and constructive feedback.

Last, but certainly by no means least, I would like to thank my parents, Andy and Margaret, my sister Nicky, and girlfriend Sophie for all the support that they have given me during the course of this research. It means more to me than I could ever write down.

## Declarations

This thesis is presented in accordance with the regulations for the degree of Doctor of Philosophy. It has been composed by myself and has not been submitted in any previous application for any degree. The work in this thesis has been undertaken by myself, except where otherwise stated.

The perspective of Empirical Modelling for educational technology is discussed in connection with constructionism in [RB02]. The restaurant manager model described in section 3.5 was discussed in [RRR00] in connection with strategic decision support systems. The digital watch model described in section 4.7 was discussed in [RBF00] in connection with engineering education. The use of Empirical Modelling to simulate LEGO Mindstorms robots described in section 6.4 was discussed in [EJR<sup>+</sup>02].

## Abstract

In this thesis, we explore the extent to which computers can provide support for domain learning. Computer support for domain learning is prominent in two main areas: in education, through model building and the use of educational software; and in the workplace, where models such as spreadsheets and prototypes are constructed. We shall argue that computer-based learning has only realised a fraction of its full potential due to the limited scope for combining domain learning with conventional computer programming. In this thesis, we identify some of the limitations in the current support that computers offer for learning, and propose Empirical Modelling (EM) as a way of overcoming them.

We shall argue that, if computers are to be successfully used for learning, they must support the widest possible range of learning activities. We introduce an Experiential Framework for Learning (EFL) within which to characterise learning activities that range from the private to the public, from the empirical to the theoretical, and from the concrete to the abstract. The term ‘experiential’ reflects a view of knowledge as rooted in personal experience. We discuss the merits of computer-based modelling methods with reference to a broad constructionist perspective on learning that encompasses bricolage and situated learning. We conclude that traditional programming practice is not well-suited to supporting bricolage and situated learning since the principles of program development inhibit the essential cognitive model building activity that informs domain learning. In contrast, the EM approach to model construction directly targets the semantic relation between the computer model and its domain referent and exploits principles that are closely related to the modeller’s emerging understanding or construal. In this way, EM serves as a uniform modelling approach to support and integrate learning activities across the entire spectrum of the EFL. This quality makes EM a particularly suitable approach for computer-based model construction to support domain learning.

In the concluding chapters of the thesis, we demonstrate the qualities of EM for educational technology with reference to practical case studies. These include: a range of EM models that have advantages over conventional educational software due to their particularly open-ended and adaptable nature and that serve to illustrate a variety of ways in which learning activities across the EFL can be supported and scaffolded.

## Abbreviations

AOP - Agent-oriented parser  
BBC - British Broadcasting Corporation  
CAI - Computer Assisted Instruction  
CPL maps - Combinatorially Piecewise Linear maps  
EDEN - Evaluator of DEfinitive Notations  
DMT - Dependency Modelling Toolkit  
DoNaLD - Definitive Notation for Line Drawing  
DTkEden - Distributed TkEden  
EDDI - Eden Definitive Database Interpreter  
EM - Empirical Modelling  
EFL - Experiential Framework for Learning  
FDL - Free Distributive Lattice  
ILE - Interactive Learning Environments  
IPPE - Instructive Portable Programming Environment  
ISBL - Information Systems Base Language  
ITS - Interactive Tutoring Systems  
MIT - Massachusetts Institute of Technology  
OO - Object-Oriented  
OpenGL - Open Graphics Library  
OXO - Noughts-and-crosses style games  
P4 - The lattice of subsets of  $\{1,2,3,4\}$   
PENGUIMS - Programmable ENvironment for Graphical User Interface  
Management and Specification  
RAT - Relational Algebra Tutor  
RCX - Robotic Command eXplorer  
RSE - Robotic Simulation Environment  
S4 - The symmetric group on 4 symbols

SASAMI - Solids Animation Simulator And Modelling Interface  
SCOUT - SScreen LayOUT notation  
SI - Spreadsheet for Images  
SIN - Situation, Ignorance, Nonsense  
SIV - Spreadsheet for Information Visualisation  
SQL - Structured Query Language  
SQLTE - SQL to EDDI translator  
SQLZERO - a variant of SQL whose semantics is consistent with relational theory  
TILT - Tools / Interfaces / Learner's needs / Tasks  
TkEden - Tk/Tcl EDEN interpreter  
UML - Unified Modelling Language  
VAT - Visual Agent Talk  
VBA - Visual Basic for Applications  
VCCS - Vehicle Cruise Control Simulator  
ZPD - Zone of Proximal Development