

---

## Relaxed Abduction

---

Thomas Hubauer

# Relaxed Abduction

Robust Information Interpretation  
for Industrial Applications

 **Springer** Vieweg

Thomas Hubauer  
München, Deutschland

Dissertation at the University of Lübeck, 2015

ISBN 978-3-658-14406-7      ISBN 978-3-658-14407-4 (eBook)  
DOI 10.1007/978-3-658-14407-4

Library of Congress Control Number: 2016942010

Springer Vieweg

© Springer Fachmedien Wiesbaden 2016

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made.

Printed on acid-free paper

This Springer Vieweg imprint is published by Springer Nature  
The registered company is Springer Fachmedien Wiesbaden GmbH

*I owe thanks to a number of people whose continued support made this thesis possible. First and foremost, I would like to express my gratefulness to my family for their encouragement and backing during these years. My thanks extend to Prof. Dr. Ralf Möller for supervising and teaching me as an external PhD candidate over many years, and to Prof. Dr. Till Tantau for his readiness to review my thesis. Last in order but definitely not least in importance, my gratitude goes to Dr. Özgür Özcep, Dr. Steffen Lamparter, and Dr. Stephan Grimm for their criticism, suggestions, and continued encouragement.*

# Preface

Automated information interpretation is gaining momentum in industrial applications. One of the major challenges in this context is the appropriate treatment of incompleteness of both the observations about the world, and the domain model formalizing it. This dissertation proposes a novel approach called "Relaxed Abduction", which is able to provide reasonable interpretations even if it would not be possible or extremely complex to explain all observations made. The approach is based on the idea of treating explanatory power and consilience of an interpretation bi-criterially instead of mapping them onto a one-dimensional scale. Based on a formalization of the proposed approach, the thesis investigates concrete instantiations and their properties (particularly runtime complexity), and proposes an extension which allows to handle incoming changes in the underlying data incrementally. Two algorithms for solving relaxed abduction problems are proposed (one generic and one  $\mathcal{EL}$ -specific) and evaluated in a real-world use case, confirming the theoretical results in practice. Additionally, to close the gap between academic research and industrial applications, the thesis proposes a methodology to structure diagnosis problems according to ISO 13379 and express it by means of several description logic knowledge bases. The dissertation results show that the proposed, flexible notion of abduction is indeed novel, relevant for industry, and permits practical usage. Future steps required to bring relaxed abduction into application are identified.

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Motivation . . . . .	1
1.2	Research Objectives . . . . .	3
1.3	Scientific Contributions . . . . .	5
1.4	Dissemination Activities . . . . .	6
1.5	Outline . . . . .	7
<b>2</b>	<b>Preliminaries</b>	<b>9</b>
2.1	Ontologies and Description Logics . . . . .	9
2.2	Abductive Reasoning . . . . .	12
2.2.1	Standard Notions of Abduction . . . . .	12
2.2.2	Concept-based Notions of Abduction . . . . .	15
2.2.3	A Critique of Logic-Based Abduction . . . . .	17
2.3	Orders . . . . .	20
2.4	Hypergraphs . . . . .	23
<b>3</b>	<b>Relaxed Abduction</b>	<b>27</b>
3.1	Formalising Diagnostics using Description Logics . . . . .	27
3.1.1	A Conceptual Model for Diagnostics . . . . .	28
3.1.2	Formalising Diagnostics in $\mathcal{EL}^+$ . . . . .	29
3.2	Formalization and Properties of Relaxed Abduction . . . . .	33
3.2.1	Bi-Criteriality of Information Interpretation . . . . .	33
3.2.2	Relaxing Logic-Based Abduction . . . . .	34
3.2.3	Instantiating Relaxed Abduction: Mapping to Dia- gnostics . . . . .	39
3.2.4	Instantiating Relaxed Abduction: Choices for $\preceq_{\mathcal{A}}$ and $\preceq_{\mathcal{O}}$ . . . . .	41
3.3	Solving Relaxed Abduction . . . . .	50
3.3.1	A Generic Solution . . . . .	51
3.3.2	A Completion-based Algorithm for $\mathcal{EL}^+$ . . . . .	55
3.3.3	Employing Pruning to Increase Efficiency . . . . .	74
3.3.4	Axiom Selection Strategies . . . . .	80

---

3.4	Extensions to the Basic Setting . . . . .	83
3.4.1	Extending Completion-based Relaxed Abduction to More Expressive DLs . . . . .	83
3.4.2	Incremental Relaxed Abduction . . . . .	93
3.5	Comparison to Alternative Approaches . . . . .	103
3.5.1	Information Interpretation and Diagnostics . . . . .	103
3.5.2	Consequence-Driven Reasoning Methods . . . . .	106
3.5.3	Truth Maintenance and Reasoning . . . . .	106
<b>4</b>	<b>Case Studies and Evaluation</b>	<b>109</b>
4.1	Implementation of the <b>RAbIT</b> System . . . . .	109
4.2	Performance and Scalability . . . . .	110
4.3	Application Scenarios and Expert Feedback . . . . .	116
4.3.1	Scenario: Turbine Diagnostics . . . . .	116
4.3.2	Scenario: Debugging of Rule-Bases . . . . .	118
<b>5</b>	<b>Conclusion</b>	<b>121</b>
5.1	Discussion of Results . . . . .	121
5.1.1	Scientific Contributions . . . . .	121
5.1.2	Practical Applications . . . . .	122
5.2	Directions for Future Work . . . . .	123

# List of Figures

2.1	Pareto-optimality and Dominance . . . . .	22
3.1	A conceptual model for diagnostics . . . . .	28
3.2	ER representation of core entities in diagnostics . . . . .	30
3.3	A hierarchy of diagnostic ontologies . . . . .	31
3.4	Normalisation rules for $\mathcal{EL}^+$ . . . . .	56
3.5	Completion rules for classification in $\mathcal{EL}^+$ . . . . .	57
3.6	Completion rules for relaxed abduction in $\mathcal{EL}^+$ . . . . .	63
3.7	Completion rules for classification in $\mathcal{EL}^{++}$ . . . . .	85
4.1	Relative runtime of RAPsolve-EL+ vs. RAPsolve-Generic . .	113
4.2	Runtime of RAPsolve-EL+ vs. scaling factor $xA$ . . . . .	114
4.3	Runtime of RAPsolve-EL+ vs. scaling factor $xA$ . . . . .	115



# List of Tables

2.1	$\mathcal{EL}^+$ syntax and semantics . . . . .	12
3.1	Relation between type of knowledge modelling, reasoning method, and application . . . . .	41
3.2	$\mathcal{EL}^{++}$ syntax and semantics . . . . .	84
3.3	Potential for improvements in efficiency by reusing information in <b>RAPsolve-Generic</b> and <b>RAPsolve-EL++</b> . . . . .	102
3.4	Comparison of related approaches . . . . .	108

# Other Listings

## List of Examples

1.1	A simple diagnostics scenario . . . . .	4
2.1	Diagnostics over incomplete domain formalisations . . . . .	17
3.1	Diagnostics over incomplete domain formalisations (cont.) . . . .	43
3.2	Subset- and simple entailment-based <b>RAP</b> are incomparable . .	45
3.3	Comparing inclusion- and cardinality-based orders . . . . .	49
3.4	Normalization . . . . .	61
3.5	Effects of Pruning . . . . .	76
3.6	Incrementality in diagnostics (updating $\mathcal{O}$ ) . . . . .	94
3.7	Incrementality in diagnostics (updating $\mathcal{T}$ ) . . . . .	95
3.8	Incrementality in diagnostics (updating $\mathcal{A}$ ) . . . . .	95
3.9	Incrementality in diagnostics (axiom migration) . . . . .	96

## List of Definitions

2.1	Logically independent axiom set . . . . .	10
2.2	Abduction problem . . . . .	14
2.3	Preferential abduction problem . . . . .	15
2.4	Subsumption-based abduction problem . . . . .	15
2.5	Pareto-optimality . . . . .	22
2.6	Directed hypergraph . . . . .	24
2.7	Monoid . . . . .	24
2.8	Directed hyperpath . . . . .	25
3.1	Relaxed abduction problem . . . . .	35
3.2	Irredundancy, dual irredundancy . . . . .	35
3.3	Strict relaxed abduction problem . . . . .	36
3.4	Entailment-based relaxed abduction problem . . . . .	45
3.5	$\mathcal{T}$ -entailment-based relaxed abduction problem . . . . .	47
3.6	Normal form for relaxed abduction problems . . . . .	58
3.7	Induced hypergraph $\mathcal{H}_{\mathbf{RAP}}$ . . . . .	62
3.8	Rooted hyperpath weight . . . . .	65
3.9	Safety of $\preceq$ for pruning . . . . .	75

## List of Theorems

2.1	Axiom-based can simulate subsumption-based abd. . . . .	16
2.2	Subsumption-based can simulate concept abd. . . . .	16
2.3	Cross product of (pre-)orders . . . . .	21
2.4	Weakly Pareto-optimal elements . . . . .	23
2.5	Strongly Pareto-optimal elements . . . . .	23
3.1	Conservativeness of the relaxation . . . . .	36
3.2	Weak Pareto-optimality of <b>RAP</b> -solutions . . . . .	37
3.3	$Sol_{\mathbf{RAP}}$ size limit for strict <b>RAP</b> . . . . .	38
3.4	Properties for inclusion-based orders . . . . .	42
3.5	(Anti-)monotonicity of preorders . . . . .	46
3.6	Properties for entailment-based orders . . . . .	46
3.7	$\mathcal{T}$ -strengthening for entailment-based orders . . . . .	47
3.8	Properties for cardinality-based orders . . . . .	48
3.9	Relaxed abduction can simulate pinpointing . . . . .	50
3.10	Correctness of <b>RAPsolve-Generic</b> . . . . .	52
3.11	Complexity of <b>RAPsolve-Generic</b> . . . . .	54
3.12	Correctness of <b>RAPnorm</b> . . . . .	60
3.13	Hyperpaths correspond to derivations . . . . .	64
3.14	Hyperpaths with minimum rooted weight are solutions . . . . .	65
3.15	Termination and correctness of <b>RAPsolve-EL+</b> . . . . .	67
3.16	Complexity of <b>RAPsolve-EL+</b> . . . . .	73
3.17	Pruning-safety of selected preorders . . . . .	75
3.18	Effects of pruning . . . . .	77
3.19	Complexity of <b>RAPsolve-ELPlus</b> with safe pruning . . . . .	79
3.20	Correctness and complexity of <b>RAPsolve-EL++</b> . . . . .	87

## List of Algorithms

3.1	RAPsolve-Generic . . . . .	52
3.2	RAPnorm . . . . .	59
3.3	RAPsolve-EL+ . . . . .	68
3.4	Procedure applyCR1 . . . . .	69
3.5	Procedure applyCR2 . . . . .	69
3.6	Procedure applyCR3 . . . . .	70
3.7	Procedure applyCR4 . . . . .	70
3.8	Procedure applyCR5 . . . . .	71
3.9	Procedure applyCR6 . . . . .	71
3.10	Function join . . . . .	72
3.11	Function meet . . . . .	72
3.12	Function meet-closure . . . . .	72
3.13	Function remove-dominated . . . . .	72
3.14	Function join-and-prune . . . . .	75
3.15	Function join-and-prune' . . . . .	78
3.16	RAPsolve-EL++ . . . . .	88
3.17	Procedure applyCR1' . . . . .	89
3.18	Procedure applyCR2' . . . . .	89
3.19	Procedure applyCR4' . . . . .	90
3.20	Procedure applyCR7 . . . . .	90
3.21	Procedure applyCR8 . . . . .	91
3.22	Procedure add-nogoods . . . . .	91
3.23	Function join-and-prune'' . . . . .	92
3.24	Function remove-dominated' . . . . .	92