

Marsden Fund Reporting

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Contact PI: Associate Professor S Link

Principal Investigators **Associate Professor S Link**
Associate Investigators
Project **Investigating complex-value database design problems
using Brouwerian algebras**
Coordinator **Mr GB Mitchell**
Institution **Massey University**

1 Summary

A key challenge in modern database research is the provision of a unified approach for the representation and efficient management of complex (that is: highly structured internally, e.g. nested) data elements. Such data occur in areas such as molecular biology, chemistry, e-business, seismology and vulcanology. While the mathematical and logical basis for traditional database systems is sufficient for dealing with unstructured data elements, strong foundations have not yet been provided for complex data elements.

In this project I pursue the observation that Brouwerian algebras provide a coherent framework for extending traditional database design solutions to encompass complex data elements. My goal is to use the theory of Brouwerian algebras to formally specify dependencies between complex data elements; to investigate how the semantics of these dependencies can be captured syntactically and processed efficiently; and to study how such dependencies can be utilised to provide syntactic guidelines for semantically well-designed databases that are free from data redundancy and processing difficulties.

The key findings of this project are as follows:

- We have been successful in proposing syntactic guidelines for semantically well-designed data that is generated from arbitrary nestings of record and list constructor. It was formally shown that our *Nested List Normal Form* is equivalent to the absence of data redundancy and update anomalies with respect to functional and multivalued dependencies. Therefore, processing difficulties are avoided with any kind of data that conforms to the syntactic structure imposed by the normal form. Moreover, it was established how to transform database schemata into such a normal form and the time-complexity for such a procedure was analysed.
- We have established a foundation for extending the synthesis approach from relational database design to complex-value databases resulting from record, list, set and multiset constructor. This may result in an algorithm that achieves a decomposition of complex-value databases that eliminates data redundancy and still preserves the exact semantics defined by its constraints.
- We have syntactically, algorithmically and logically characterised the interactions of weak functional dependencies in the presence of record, list and disjoint union constructor. This has established a foundation for a future normal form proposal of complex-value databases resulting from these type constructors.
- We have proven a precise connection between the consequence relation of Boolean and multivalued dependencies in the presence of record, list, set and multiset constructor and the logical consequence relation of certain fragments of Boolean propositional logic. These findings extend well-known results from relational databases to databases which are not in first normal form, i.e., which are nested. The database designer can take advantage of these equivalences to reduce database design problems to well-studied problems in Boolean propositional logic.
- We developed algorithms that compute a set of XML functional dependencies which implies precisely those XML functional dependencies satisfied by a given XML document. This helps to extract interesting patterns of existing XML data and provides invaluable information for the design process of XML databases.

The investigations also resulted in the following findings for relational databases that were not anticipated before:

- Biskup showed a trade-off result at the beginning of the 1980s stating that in order to capture the implication of multivalued dependencies one cannot weaken two particular syntactic inference rules at the same time without losing completeness. However, our investigations showed that it is indeed possible to weaken both of these rules in case one does consider inference rules that Biskup neglected to consider at that time.
- I have investigated Biskup's alternative notion of implication for multivalued dependencies in relational databases (both with and without null values) where the underlying set of attributes is left undetermined. I was able to identify all axiomatisations for this notion and studied the time-complexity of the associated implication problem, respectively.
- We have further extended this notion of implication to the class of full hierarchical dependencies which properly subsume multivalued dependencies. We were able to establish an axiomatisation for this notion of implication. Biskup and I also investigated the combined class of functional and full hierarchical dependencies, and established a classification of axiomatisations with respect to how well the semantics of these dependencies is syntactically represented.

The study of the type constructors also resulted in the following findings for conceptual database design:

- We introduced the collection types of rankings, lists, sets and bags into the formal framework of Entity-Relationship modeling. This provides users with easy-to-use constructors that naturally model different kinds of collections of the same object type. Moreover, we propose a transformation of such extended ER schemata into relational database schemata.
- Based on these collection types and based on the Extended Entity-Relationship model we have revised Peter Chen's basic guidelines for converting English sentence structures into a conceptual data model.
- We have devised a new technique that assists designers in deciding whether a constraint expresses a desirable property of the application at hand or not. This technique utilises propositional tableaux to semi-automatically generate sample databases which the designer and user can inspect for its meaningfulness.

2 Introduction

This section is the original outline of my objectives for this project:

In my PhD thesis I proposed a classification of data models according to the type constructors that are supported by the models. This permits the study of database design problems with respect to various classes of dependencies in the presence of certain combinations of type constructors. My original observation was that *Brouwerian algebras* form a mathematically-sound foundation for this investigation. This is perhaps surprising since Brouwerian algebras were originally introduced to investigate connections between algebra and topology. Brouwerian algebras subsume Boolean algebras which are fundamental to the success of the relational model of data. The objectives that I want to address in this project are:

1. *Normal Forms and Types*: I want to develop analogues of Third and Fourth *normal form proposals* that cover complex data generated by applications of particular combinations of record, list, set, multiset and union constructors. This was noted as an open problem. In particular, I want to emphasise the *semantic justification* of my proposals. An important follow-up problem is how to achieve such a normal form in practice. Therefore, I will develop schema transformation algorithms that attain similar transformations as the *decomposition* and *synthesis* approach from relational database design. I will also try to identify *pivoting* as an effective transformation strategy in the presence of complex data elements. Throughout this phase of research, I see the analysis of the union constructor as a particular challenge.
2. *Logical Characterisation*: I want to establish precise connections between the implication of dependencies and *logical consequence relations* in particular logics. This would generalise important results from relational databases and describe the impact of type constructors from a logical point of view. Furthermore, I will pursue a *topological approach* towards an interpretation of dependencies which is based on the representation of finite distributive lattices via PO-spaces. I consider these objectives extremely important since they may permit the use of invaluable tools from algebra, logic and topology to assist with future investigations of dependencies.
3. *Dependency Mining and Approximation*: I will address the problem of *dependency inference* in complex-value databases utilising nested attributes. The problem is that of finding a set of dependencies which implies precisely those dependencies satisfied by a given database instance. I intend to develop algorithmic solutions to this problem which will provide insight into the structure and patterns of the database instance under investigation. *Approximate dependencies*, i.e., those dependencies that are *almost* satisfied by a database instance, are closely related. While dependency inference and approximate dependencies have been studied intensely for the relational data model, they have not yet received any attention in the presence of complex data elements. The framework provided by Brouwerian algebras is also suitable for addressing these issues.

3 Progress

3.1 Normal Forms and Types

The objectives stated in item one above have been achieved, but not in their full generality. I was successful in extending the Fourth normal form proposal together with its semantic justification to the presence of both record and list constructor. Moreover, I have shown how to transform database schemata into Fourth normal form schemata, and analysed the time-complexity of this transformation. In this sense, the objectives have been realised completely for both record and list constructor. The results have been published in Springer's *Lecture Notes in Computer Science*, and were presented at the *4th International Symposium on Foundations of Information and Knowledge Systems* at Budapest, Hungary. A journal version entitled *The Nested List Normal Form* will be submitted this year.

In the meantime, the axiomatisation of functional and multivalued dependencies in databases generated by record and list constructor has been published in Springer's *Annals of Mathematics and Artificial Intelligence*. We have also developed a provably efficient and correct algorithm that decides the implication of functional dependencies in the presence of record, list, set and multiset constructor. These findings have been published in Elsevier's *Theoretical Computer*

Science.

While Boyce-Codd and Fourth normal form always result in the absence of data redundancy, the output schema is lossless (no new data is added nor is any data lost) but may not preserve the exact semantics of the input schema (the transformation is not dependency-preserving). The Third Normal Form proposal in relational databases always achieves a lossless, dependency-preserving decomposition, but may not eliminate all data redundancy. It is based on the fact that a dependency-preserving decomposition is lossless precisely when it contains a key. However, the result is only valid when the domains of the attributes are infinite. Henning Köhler and I have extended this result to the case where attributes in the left-hand side of functional dependencies have infinite domains. We then succeeded in generalising the theorem to complex-value databases which result from arbitrary finite nestings of record, list, set and multiset constructor. This establishes a foundation for extending the Third normal form proposal (known as the synthesis approach) from relational to complex-value databases. The results have been published by Springer's *Lecture Notes in Computer Science*, and were presented at the *5th International Symposium on Foundations of Information and Knowledge Systems* at Pisa, Italy.

We have started to address the *union* constructor as well. The behaviour of the union constructor naturally pushes the investigation of *weak functional dependencies*. While functional dependencies correspond to the linear-time decidable fragment of Horn clauses in propositional logic, weak functional dependencies take advantage of arbitrary clauses, and therefore represent full propositional reasoning in databases. In relational databases the class of weak functional dependencies is finitely axiomatisable and the associated implication problem is *coNP*-complete in general. We extended this axiomatisation to databases in which complex elements can be derived from atomic ones by finitely many nestings of record, list and *disjoint union* constructor. In particular, we constructed two nested tuples that can serve as a counterexample relation for the implication of weak functional dependencies. We further apply this construction to show an equivalence to truth assignments that serve as counterexamples for the implication of propositional clauses. Hence, we characterised the implication of weak functional dependencies in complex-value databases in completely logical terms. Consequently, state-of-the-art SAT solvers can be applied to reason about weak functional dependencies in relational and complex-value databases. These results are in line with those objectives outlined in the next subsection as well. An article reporting these findings is currently under review at the *Journal of Universal Computer Science*.

3.2 Logical Characterisation

The objectives of the second item have been achieved completely. I have investigated functional and more generally Boolean dependencies in the presence of record, list, set and multiset constructor, as well as multivalued dependencies in the presence of record and list constructor. For Boolean dependencies I have proven that their implication is captured by the logical consequence relation of Boolean propositional formulae, where in particular functional dependencies correspond to Horn clauses. The implication of multivalued dependencies is equivalent to the logical implication of disjunctions of literals where at least two are positive. Some results have been presented at the *17th Australasian Database Conference* at Hobart, Australia. All findings have been published by Elsevier's *Annals of Pure and Applied Logic*.

As mentioned before, we also succeeded in giving a logical characterisation of weak functional dependencies in the presence of records, lists and disjoint unions. This was not planned originally. The characterisation also implies that algorithmic solutions for the implication prob-

lem in propositional logic can be applied to solve the implication problem for weak functional dependencies.

3.3 Dependency Mining and Approximation

The problem of approximate dependencies in complex-value databases has not been addressed so far due to lack of time. Instead, the additional work reported in the next section was given priority. The reason for this is that relational databases have been well-investigated, and new findings are hard to come by. However, the studies in this project led to surprising new insights (at least the author believes so).

The problem of *dependency inference* was addressed by Ms Thu Trinh who is currently finishing up her PhD under the supervision of Sven Hartmann and myself. She developed algorithms that compute a set of functional dependencies which implies precisely those dependencies satisfied by a given database instance. The underlying database model was the eXtensible Markup Language (XML). XML data is nested, and interesting to study with respect to the semantics of the collection type constructors involved. Thu based her studies on multisets, the most general constructor since it does not put any constraints on neither order nor multiplicity. Thu was successful in extending hypergraph-based approaches for dependency inference from relational to XML databases. Her findings can also be translated into the framework of nested attributes. The results have been published in Springer's *Lecture Notes in Computer Science*, and been reported at the *5th International Symposium on Foundations of Information and Knowledge Systems* in Pisa, Italy.

4 Additional Work

4.1 New Findings for the Relational Model of Data

The research has had some surprising new insight into multivalued dependencies in the relational model of data as introduced by Fagin, Delobel and Zaniolo. Biskup showed a trade-off result at the beginning of the 1980s stating that in order to capture the implication of these multivalued dependencies one cannot weaken two particular syntactic inference rules at the same time without losing completeness. However, our investigations showed that it is indeed possible to weaken both of these rules in case one does consider inference rules that Biskup neglected to consider at that time. These findings have been published in Elsevier's *Theoretical Computer Science*, and the corresponding article *On a Problem of Fagin concerning multivalued dependencies in relational databases* was reported as 13th most downloaded article within the period of January to March 2006.

Furthermore, I have investigated Biskup's alternative notion of implication for multivalued dependencies in relational databases in which the underlying set of attributes is left undetermined. I was able to determine all axiomatisations for this notion and studied the time-complexity of the associated implication problem. These results were published by Springer's *Lecture Notes in Computer Science*, and were presented at the *4th International Symposium on Foundations of Information and Knowledge Systems* at Budapest, Hungary. Currently, the journal version of this paper is under review at Springer's *Acta Informatica*.

Sven Hartmann, Henning Köhler and myself have further extended Biskup's notion of implication to the class of full hierarchical dependencies which properly subsume multivalued dependencies. We were able to establish an axiomatisation for this notion of implication. These results are published by Springer's *Annals of Mathematics and Artificial Intelligence*.

I have also extended Biskup's notion of implication to multivalued dependencies in incomplete database relations in which null values may be present. I succeeded in providing an axiomatisation, and a new notion of minimality. The results were reported at the *12th Computing: the Australasian Theory Symposium* at Hobart, Australia; as well as the *17th International Workshop on Database and Expert Systems Applications* at Krakow, Poland. The findings have also been accepted by World Scientific's *International Journal on Foundations of Computer Science*, and will be published shortly.

Finally, Biskup and I together investigated the combined class of functional and full hierarchical dependencies. We established an axiomatisation which clarifies the role of the complementation rule in the combined setting. In fact, we identify inference systems that are appropriate in the following sense: full hierarchical dependencies can be inferred without use of the complementation rule at all or with a single application of the complementation rule at the final step of the inference; and functional dependencies can be inferred without any application of the complementation rule. Furthermore, we established a finite axiomatisation for functional and full hierarchical dependencies in undetermined universes. These results were presented at the *5th International Symposium on Foundations of Information and Knowledge Systems* at Pisa, Italy. Currently, I am working on a journal version of this paper.

4.2 New Findings for Conceptual Data Models

Our studies of collection types has strengthened our belief that collections play an important part in everyday life. Therefore, conceptual data models should support collection types in order to make data modeling as natural as possible for its users. Based on the fundamental properties of endorsing order and multiplicity of its elements we introduced the collection types of rankings, lists, sets and bags into the formal framework of Entity-Relationship modeling. This provides users with easy-to-use constructors that naturally model different kinds of collections of the same object type. Moreover, we proposed a transformation of such extended ER schemata into relational database schemata. The transformation is intuitive and invertible introducing surrogate attributes that preserve the semantics of the collection. Furthermore, the transformation is a proper extension of the current standard, and results in a relational database schema that is in Inclusion Dependency Normal Form with respect to its functional and inclusion dependencies. In addition, we introduce a uniqueness constraint that identifies collections uniquely and guarantees referential integrity at the same time. These findings were published by Springer's *Lecture Notes in Computer Science*, and were presented at the *26th International Conference on Conceptual Modeling* at Auckland, New Zealand.

An input to the conceptual database design phase contains a description of the target database. This description is usually given in some natural language, for instance in English. Conceptual design aims at transforming English sentences into a conceptual database schema. A conceptual data model should therefore possess modeling features that can represent English sentence structures. Since Peter Chen himself has argued that the basic ER model has such constructs many extensions of this basic ER model have been proposed. Based on these new features we have revised the several correspondences between English sentence structures and concepts of ER modeling. It turns out that Extended ER modeling can provide both a well-defined semantics and improved modeling elements that naturally reflect English language sentence structures. Collection type constructors form one of these extensions, and again, our studies in the project resulted in these findings. The results were published in *Conferences in Research and Practice in Information Technology* and received the Best Paper Award at the *4th Asia-Pacific Conference on Conceptual Modeling* at Ballarat, Australia. Currently, we are

working on a journal version.

Our studies on connections between logics and data dependencies made us realise that propositional tableaux techniques can assist the database designer in deciding whether a dependency expresses some desirable semantic property of the application at hand or not. We identified established tableaux techniques as an invaluable tool for semantic knowledge acquisition in the design process of relational databases. Sample databases allow users and designers to judge, justify, convey and test their understanding of the semantics of the future database. In the case of integrity constraints such sample data can provide considerable assistance for deciding whether a constraint captures desirable information about the database or not. Since constraints can be particularly difficult to grasp in practice sample databases offer a convenient tool to confirm or reject the usefulness of potential candidate constraints. We have pinpointed the Chase and analytical tableau as two tableaux techniques that are able to automatically generate sample databases for large classes of integrity constraints. The Chase can be used for generating sample data that allows us to reject candidate constraints. However, analytical tableaux enable us to find all minimal sample databases which enable us to either accept or reject a candidate constraint. These results were published in *Conferences in Research and Practice in Information Technology* and were presented at the *5th Asia-Pacific Conference on Conceptual Modeling* at Wollongong, Australia. We have received an invitation to submit a journal version to the *Journal of Research and Practice in Information Technology*.

5 Future Work

5.1 Original Objectives

Not all goals of the original proposal have been completely addressed yet.

For instance, we have not yet proposed any normal forms that address the presence of set, multiset and union constructor. It is an open problem to extend the entire range of normalisation theory from relational databases to interesting combinations of such type constructors. There are also normal form proposals that differ from Boyce-Codd, Third and Fourth Normal Form from relational database design theory. So far, we have also not investigated which role pivoting can play in decomposing complex-value database schemata.

We have also not been able to address approximate dependencies yet, i.e., those dependencies that are *almost* satisfied by a database instance (e.g. the first name functionally determines the sex). The literature suggests a great number of approximation measures suitable for different application domains, and it can be explored what kind of measures are suitable for which combinations of type constructors.

5.2 Framework of Nested Attributes

Apart from this project, Brouwerian algebras have not been explored as a foundation for the field of databases. Consequently, there are several opportunities to analyse their suitability for many other areas of database research.

One may want to increase the expressiveness of schemata while maintaining their underlying algebraic structure. Moreover, one should explore the possibility of defining constraints on embedded nested attributes, i.e., those nested attributes which form a substring of another one. The interaction of constraints on different embedded attributes may be worthwhile to analyse in detail.

The entire area of query languages, query processing and query optimisation could potentially be investigated in the context of nested attributes. It seems desirable to define SQL-like query languages in this context, but also extend relational algebra and calculus from relational databases to complex-value ones. Physical database tuning using indexing and appropriate data structures is a long-standing open problem for database models with complex type constructors.

The findings of this research should be made applicable to popular data models such as existing object-oriented and semi-structured data models including XML. However, the peculiarities of these models enforce additional issues on those encountered in the general model of nested attributes.

5.3 Extending Findings of Additional Work

The results reported in the section on additional work should also be extended in the future.

The issues that have been studied for functional, multivalued and full hierarchical dependencies in relational databases also exist in other data models for which these dependencies have been defined, e.g. in temporal, spatial and fuzzy databases as well as XML. Due to the popularity of these models and their increased expressiveness it is a challenge to extend the current results to such settings.

Since we have introduced collection types into the formal Entity-Relationship model there are several further directions that can be explored. The transformations that encode Entity-Relationship schemata into schemata of various other data models need to be extended to cover collection types as well. Cardinality constraints form an important class of conceptual constraints which have not been explored in the presence of collection types.

The revised guidelines for converting English text into conceptual data models provide a general understanding for the necessity of features a conceptual data model should possess. The guidelines explain why and how conceptual data models can be used to formalise a first approximation of the target database. In general, however, it is impossible to apply these guidelines automatically. Therefore, the rules must be refined and restricted such that semi-automatic tools can be built. Advanced natural language processing will become necessary.

Since we have successfully applied propositional tableaux to generate sample databases that assist in the acquisition of dependencies, it seems reasonable to investigate first-order tableaux as well. These might be helpful when more expressive constraints are under investigation.

6 Financial Review

A financial report will be provided by our research office when all transactions have been processed.

B Popular Categories

information technology

C Sharing Knowledge

Publications - Book Chapter

Status	Chapter Title	Book Title
Published	The Nested List Normal Form for functional and multivalued dependencies Editor: Dix, Hegner	Foundations of Information and Knowledge Systems (FoIKS) Publisher: Springer
ID: 13300-4	City: Berlin Year: 2006 Authors: Hartmann S, Link S	Page: 135-156
Published	On multivalued dependencies in fixed and undetermined universes Editor: Dix, Hegner	Foundations of Information and Knowledge Systems (FoIKS) Publisher: Springer
ID: 13301-5	City: Berlin Year: 2006 Authors: Link S	Page: 257-276
Published	Collection Type Constructors in Entity-Relationship Modeling Editor: Christine Parent, Klaus-Dieter Schewe, Veda C. Storey, Bernhard Thalheim	Conceptual Modeling - ER 2007 Publisher: Springer Lecture Notes in Computer Science
ID: 0-24	City: Heidelberg Year: 2007 Authors: Hartmann S, Link S	Page: 307-322
Published	Appropriate Reasoning about Data Dependencies in Fixed and Undetermined Universes Editor: Sven Hartmann, Gabriele Kern-Isberner	Foundations of Information and Knowledge Systems - FoIKS 2008 Publisher: Springer Lecture Notes in Computer Science
ID: 0-25	City: Heidelberg Year: 2008 Authors: Biskup J, Link S	Page: 58-77
Published	Lossless Decompositions in Complex-valued Databases Editor: Sven Hartmann, Gabriele Kern-Isberner	Foundations of Information and Knowledge Systems - FoIKS 2008 Publisher: Springer Lecture Notes in Computer Science
ID: 0-26	City: Heidelberg Year: 2008 Authors: Koehler H, Link S	Page: 329-347
Published	Using Transversals for Discovering XML Functional Dependencies Editor: Sven Hartmann, Gabriele Kern-Isberner	Foundations of Information and Knowledge Systems - FoIKS 2008 Publisher: Springer Lecture Notes in Computer Science
ID: 0-32	City: Heidelberg Year: 2008 Authors: Trinh T	Page: 199-218

Publications - Conference Presentation

Status	Title	Conference
Contributed Talk	On multivalued dependencies in fixed and undetermined universes	Foundations of Information and Knowledge Systems, FoIKS
ID: 13306-10	Place: Budapest, Hungary Year: 2006 Authors: Link S	Date: Feb

Publications - Conference Presentation

Status	Title	Conference
Contributed Talk ID: 13307-11	The Nested List Normal Form for functional and multivalued dependencies Place: Budapest, Hungary Year: 2006 Authors: Hartmann S, Link S	Foundations of Information and Knowledge Systems Date: Feb
Contributed Talk ID: 13308-12	Horn clauses and functional dependencies in complex-value databases Place: Hobart, Australia Year: 2006 Authors: Hartmann S, Link S	17th Australasian Database Conference Date: Jan
Contributed Talk ID: 13309-13	On the logical implication of multivalued dependencies with null values Place: Hobart, Australia Year: 2006 Authors: Link S	12th Computing: The Australasian Theory Symposium Date: Jan
Contributed Talk ID: 13310-14	A strongly minimal axiomatisation of multivalued dependencies in incomplete database relations Place: Krakow, Poland Year: 2006 Authors: Link S	17th International Workshop on Database and Expert Systems Applications Date: Sep
Contributed Talk ID: 13311-15	On Inferences of Full Hierarchical Dependencies Place: Ballarat, Australia Year: 2007 Authors: Hartmann S, Link S	30th Australasian Computer Science Conference Date: Feb
Contributed Talk ID: 0-27	English Sentence Structures and EER Modeling Place: Ballarat, Australia Year: 2007 Authors: Hartmann S, Link S	Asia-Pacific Conference on Conceptual Modeling Date: Jan
Contributed Talk ID: 0-28	Collection Type Constructors in Entity-Relationship Modeling Place: Auckland, New Zealand Year: 2007 Authors: Hartmann S, Link S	Conceptual Modeling 2007 Date: Nov
Contributed Talk ID: 0-29	Constraint Acquisition - You can Chase but you cannot find Place: Ballarat Year: 2008 Authors: Hartmann S, Link S, Trinh T	Asia-Pacific Conference on Conceptual Modeling 2008 Date: Jan
Contributed Talk ID: 0-30	Appropriate Reasoning about Data Dependencies in Fixed and Undetermined Universes Place: Pisa, Italy Year: 2008 Authors: Biskup J, Link S	Foundations of Information and Knowledge Systems - FolKS 2008 Date: Feb

Publications - Conference Presentation

Status	Title	Conference
Contributed Talk ID: 0-31	Lossless Decompositions in Complex-valued Databases Place: Pisa, Italy Year: 2008 Authors: Koehler H, Link S	Foundations of Information and Knowledge Systems - FoIKS 2008 Date: Feb
Contributed Talk ID: 0-33	Using Transversals for Discovering XML Functional Dependencies Place: Pisa, Italy Year: 2008 Authors: Trinh T	Foundations of Information and Knowledge Systems - FoIKS 2008 Date: Feb

Publications - Paper

Status	Title of Paper	Journal	Volume
Published ID: 13297-1	On a problem of Fagin concerning multivalued dependencies in relational databases Year: 2006 Authors: Hartmann S, Link S	Theoretical Computer Science Page: 53-62	353
Published ID: 13298-2	Functional and multivalued dependencies in nested databases generated by record and list constructor Year: 2006 Authors: Hartmann S, Link S, Schewe KD	Annals of Mathematics and Artificial Intelligence Page: 114-164	46
Published ID: 13299-3	Deciding the implication of functional dependencies in complex-value databases Year: 2006 Authors: Hartmann S, Link S	Theoretical Computer Science Page: 212-240	364
Published ID: 0-16	Full Hierarchical Dependencies in Fixed and Undetermined Universes Year: 2007 Authors: Hartmann S, Koehler H, Link S	Annals of Mathematics and Artificial Intelligence Page: 195-226	50
Published ID: 0-17	Characterising nested database dependencies by fragments of propositional logic Year: 2008 Authors: Hartmann S, Link S	Annals of Pure and Applied Logic Page: 84-106	152(1-3)
Submitted ID: 0-19	Charting the Completeness Frontier of Inference Systems for Multivalued Dependencies Year: 0 Authors: Link S	Acta Informatica Page:	
In Press ID: 0-20	On the implication of multivalued dependencies in partial database relations Year: 0 Authors:	International Journal on Foundations of Computer Science Page:	

Publications - Paper

Status	Title of Paper	Journal	Volume
Submitted	Weak Functional Dependencies - Full Propositional Expressiveness for the Database Practitioner	Journal of Universal Computer Science	
ID: 0-21	Year: 0 Authors: Hartmann S, Link S	Page:	
In Preparation	The Nested List Normal Form	Fundamenta Informaticae	
ID: 0-34	Year: 0 Authors: Hartmann S, Link S	Page:	
In Preparation	Appropriate Inference Systems for Functional and Full Hierarchical Dependencies	Annals of Mathematics and Artificial Intelligence	
ID: 0-35	Year: 0 Authors: Biskup J, Link S	Page:	
In Preparation	Correspondences between English Sentence Structures and EER Diagrams	Journal of Research and Practice in Information Technology	
ID: 0-36	Year: 0 Authors: Hartmann S, Link S	Page:	
In Preparation	Assisting Constraint Acquisition by Propositional Tableaux	Journal of Research and Practice in Information Technology	
ID: 0-37	Year: 0 Authors: Hartmann S, Link S, Trinh T	Page:	

Publications - Refereed Conference Proceedings

Status	Title of Paper	Title of Proceedings	Volume	Page
Published	On Inferences of Full Hierarchical Dependencies Editor: Dobbie G	30th Australasian Computer Science Conference		
ID: 13305-9	Year: 2006 Authors: Hartmann S, Link S	Publisher: Conferences in Research and Practice in Information Technology	Volume: 62	Page: 69-78
Published	Horn clauses and functional dependencies in complex-value databases Editor: Bailey, Dobbie	17th Australasian Database Conference (ADC)		
ID: 13302-6	Year: 2006 Authors: Hartmann S, Link S	Publisher: Conferences in Research and Practice in Information Technology	Volume: 49	Page: 21-30
Published	On the logical implication of multivalued dependencies with null values Editor: Jay, Gudmundsson	12th Computing: The Australasian Theory Symposium		
ID: 13303-7	Year: 2006 Authors: Link S	Publisher: Conferences in Research and Practice in Information Technology	Volume: 51	Page: 113-122

Publications - Refereed Conference Proceedings

Status	Title of Paper	Title of Proceedings
Published	A strongly minimal axiomatisation of multivalued dependencies in incomplete database relations Editor: Christiansen, Martinenghi	17th International Workshop on Database and Expert Systems Applications Publisher: IEEE
ID: 13304-8	Year: 2006 Authors: Link S	Volume: Page: 537-541
Published	English Sentence Structures and EER Modeling Editor: John F. Roddick, Annika Hinze	Conferences in Research and Practice in Information Technology Publisher: Australian Computer Society
ID: 0-22	Year: 2007 Authors: Hartmann S, Link S	Volume: 67 Page: 27-35
Published	Constraint Acquisition - You can Chase but you cannot find Editor: Annika Hinze, Markus Kirchberg	Conferences in Research and Practice in Information Technology Publisher: Australian Computer Society
ID: 0-23	Year: 2008 Authors: Hartmann S, Link S, Trinh T	Volume: 79 Page: 59-68

D Personnel

Postdoctoral, PhD & Masters Students

Name	Role	FTE
Henning Koehler	PhD	0
Thu Trinh	PhD	0

E Flow-on Effects & Activities

Collaboration

Collaborator	Institution	Country	Nature of Collaboration
Sven Hartmann	Dept of Information Systems	New Zealand	Joint Research
Joachim Biskup	University of Dortmund	Germany	Joint Research

Awards

Researcher	Award
Sven Hartmann, Sebastian Link	Best Paper Award - Asia Pacific Conference on Conceptual Modeling 2007
Sebastian Link	Early Career Award for Distinction in Research - Massey 2006