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Aims and Scope
The periodical *Dagstuhl Reports* documents the program and the results of Dagstuhl Seminars and Dagstuhl Perspectives Workshops.
In principal, for each Dagstuhl Seminar or Dagstuhl Perspectives Workshop a report is published that contains the following:

- an executive summary of the seminar program and the fundamental results,
- an overview of the talks given during the seminar (summarized as talk abstracts), and
- summaries from working groups (if applicable).

This basic framework can be extended by suitable contributions that are related to the program of the seminar, e.g. summaries from panel discussions or open problem sessions.

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Report from Dagstuhl Seminar 14061

Statistical Techniques for Translating to Morphologically Rich Languages

Edited by

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Abstract

This report documents the program and the outcomes of Dagstuhl Seminar 14061 "Statistical Techniques for Translating to Morphologically Rich Languages". The seminar took place in February 2014. The purpose of the seminar was to allow disparate communities working on problems related to morphologically rich languages to meet to discuss an important research problem, translation to morphologically rich languages. While statistical techniques for machine translation have made significant progress in the last 20 years, results for translating to morphologically rich languages are still mixed versus previous generation rule-based systems, so this is a critical and timely topic. Current research in statistical techniques for translating to morphologically rich languages varies greatly in the amount of linguistic knowledge used and the form of this linguistic knowledge. This varies most strongly by target language, for instance the resources currently used for translating to Czech are very different from those used for translating to German. The seminar met a pressing need to discuss the issues involved in these translation tasks in a more broad venue than the ACL Workshops on Machine Translation, which are primarily attended by statistical machine translation researchers. The report describes the introductory material presented to the group, the organization of break-out discussion groups by topic, and the results of the seminar.

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1 Executive Summary

Alexander Fraser
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Hans Uszkoreit

This report documents the program and the outcomes of Dagstuhl Seminar 14061 "Statistical Techniques for Translating to Morphologically Rich Languages". The website of the seminar, which allows access to most of the materials created for and during the seminar, is http://www.dagstuhl.de/14061. The seminar on Statistical Techniques for Translating to Morphologically Rich Languages allowed disparate communities working on problems related to morphologically rich languages to meet to discuss an important research problem, translation to morphologically rich languages. While statistical techniques for machine translation have made significant progress in the last 20 years, results for translating to morphologically rich languages are still mixed versus previous generation rule-based systems, so this is a critical and timely topic. Current research in statistical techniques for translating to morphologically rich languages varies greatly in the amount of linguistic knowledge used and the form of this linguistic knowledge. This varies most strongly by target language, for instance the resources currently used for translating to Czech are very different from those used for translating to German. The seminar met a pressing need to discuss the issues involved in these translation tasks in a more broad venue than the ACL Workshops on Machine Translation, which are primarily attended by statistical machine translation researchers.

Important background for the discussion was the recent realization that more linguistically sophisticated methods are required to solve many of the problems of translating to morphologically rich languages. Therefore it was critically important that SMT[1] researchers be able to interact with experts in statistical parsing and morphology who work with morphologically rich languages to discuss what sort of representations of linguistic features are appropriate and which linguistic features can be accurately determined by state of the art disambiguation techniques. This was an important step in creating a new community crossing these research areas. Additionally, a few experts in structured prediction were invited. The discussions took advantage of their insight in how to jointly model some of these phenomena, rather than combining separate tools in ad-hoc pipelines as is currently done. The overall discussion was driven by the following questions:

- Which linguistic features (from syntax, morphology and other areas such as coreference resolution) need to be modeled in SMT?
- Which statistical models and tools should be used to annotate linguistic features on training data useful for SMT modeling?
- How can we integrate these features into existing SMT models?
- Which structured prediction techniques and types of features are appropriate for training the extended models and determining the best output translations?
- What data sets should be used to allow a common test bed for evaluation?

[1] SMT – Statistical Machine Translation

- How should evaluation be conducted, given the poor results of current automatic evaluation metrics on morphologically rich languages?

The Dagstuhl seminar on Statistical Techniques for Translating to Morphologically Rich Languages addressed these questions by allowing four different communities to meet together: statistical machine translation, statistical parsing, morphology and structured prediction.

Outcome in brief. The Dagstuhl seminar on Statistical Techniques for Translating to Morphologically Rich Languages was a great success. The discussions held will play an important role in allowing researchers to significantly advance the state-of-the-art. In particular, strong and weak points in current research approaches were identified and proposals to address the weak points were made. In addition, the seminar acted as a valuable venue for more junior researchers to spend more time talking with senior researchers than is possible in a conference setting. Finally, several new community building ideas were discussed, including a DFG proposal connecting all of the major sites for statistical machine translation research in Germany, see below.

Invited Talks. We begin the detailed discussion with a brief idea about the three invited keynote talks (as well as the introductory overview and motivational talk). All of these talks were very well received, with several seminar participants commenting that they learned a significant amount by being able to see a synthesis of the problems, current approaches and possible future approaches to translating to morphologically rich languages. The three keynote talks were:

- Philipp Koehn of the University of Edinburgh presented a general discussion of dealing with the phenomena of morphologically rich languages in translation.
- Kristina Toutanova of Microsoft Research presented a detailed overview of the state-of-the-art in statistical machine translation research related to morphologically rich languages in translation.
- Kevin Knight of the University of Southern California presented a vision of the future, where the field could go, in terms of both better modelling of morphologically rich languages, and the use of more language independent structure (at the semantic level) in translation.

After this, people interested in leading a discussion group held talks.

Discussion Groups. There were initially nine proposed topics for discussion groups (note that these are listed as topic-focused talks subsequently in the report):

- Nivre/Petrov: Parallel dependency treebanks and linguistic resources
- Tiedemann: The use of synthetic training data and pivot languages to overcome data sparseness
- Kirchhoff: Language modeling
- Dyer: Modeling morphemes vs. modeling words and smoothing with morphemes
- Habash: Arabic morphology and deep morphology representation for MT
- Williams/Koehn: Syntactic SMT for morphologically rich languages
- Knight: Semantics
- Webber: Discourse/aspects of semantics
- Bojar/Hajič: Generating morphology for SMT

Following this all participants emailed the organizers with their discussion group preferences. In the end, all but two participants were assigned to their first preference. We eliminated two groups (on synthetic training data and generating morphology), and their proposers joined other groups.

Following initial group presentations by some groups on Wednesday morning, three groups dissolved and several decided to continue. The three new groups that were proposed were:

- Virpiojia/Dyer: Unsupervised morphology for statistical machine translation
- Wu/Lavie: Evaluation of machine translation output
- Nivre/Knight: Universal Annotation and Abstract Meaning Representation

Highlights of what was accomplished by the discussion groups were:

- Dyer and Virpiojia and groups looked at morphologically aware translation models which use morphology to cover the long-tail without requiring morphological modelling of very frequent tokens, and looked at the state-of-the-art in unsupervised modeling.
- Kirchhoff and her group carried out a detailed survey of the state-of-the-art for language modeling of morphologically rich languages and documented this on the Wiki.
- Nivre and his two groups (one co-led with Petrov) defined a new proposed annotation standard for working on two levels (surface forms and lemmas, including multi-word-entities and decomposed compounds).
- Habash and his group carried out a literature review of attempts to deal with Arabic morphology in translation, discussing the strengths and weaknesses of the approaches, and identifying a new direction for future work.
- Williams, Koehn and group looked at the application of unification to modelling agreement in multiple languages.
- Knight and his two groups worked on general applications of semantically-aware processing to morphologically rich languages and on identifying areas where the Abstract Meaning Representation could be applied to this problem.
- Webber and group created a list of resources and research papers on applying discourse modeling to statistical machine translation and looked at machine translation output to find errors caused by broken discourse constraints.
- Wu, Lavie and group discussed and documented the different levels of linguistic analysis required for high quality automatic evaluation when the target language is morphologically rich.

See the individual abstracts for more information and further details.

Other activities. In addition to the formal work carried out in the talks and discussion groups, Dagstuhl offered an intimate environment strongly encouraging networking and discussion. The meal system of Dagstuhl, with random assignment of people to tables, is an excellent idea and was particularly useful for the more junior participants who did not know many of the senior researchers attending (several people mentioned informally that this was the best experience of this sort they have had). The informal evening activities centering around social gatherings and the music room were also very well attended and a variety of interesting discussions took place. The excursion to Trier was a welcome mid-week break and provided another networking opportunity, as well as being highly interesting for the vast majority of participants who had not previously visited a city with a similar historical background.

The seminar was unusual for Dagstuhl itself in that very few of the participants had participated in a Dagstuhl seminar previously. Due to the strongly positive reaction we anticipate that other research areas within Natural Language Processing will apply for Dagstuhl seminars.

We would like to take the opportunity here to thank Dagstuhl for the wonderful logistic support and for providing such a stimulating environment for our work.

Communities represented in more detail. The seminar was a success in terms of the strong participation of women and a good geographical distribution (although Asia could have been somewhat more strongly represented). Our only strong area of concern was that of the numerous participants from companies invited, only two attended (Kristina Toutanova of Microsoft Research and Slav Petrov of Google, who gave one of the keynotes and co-led a discussion group respectively). Nevertheless the networking opportunities were excellent and many participants informally told us that this was an excellent meeting which they expected to have a strong impact on their research.

One characteristic of the proposal which was successfully carried out was a meeting of four different communities: statistical machine translation, statistical parsing, morphology and structured prediction. In particular, we felt that the interaction between the statistical machine translation researchers and the researchers working on statistical parsing and morphology was highly productive and will likely lead to new techniques of analyzing morphologically rich languages which will be more useful in translation research than the current approaches. We believe that the Dagstuhl seminar has been unique in terms of providing the opportunity for these communities to meet together for five days and understand each others' perspective on research.

Conclusion and Impact. In conclusion, we believe the Dagstuhl seminar has met the goals we set out for it, in terms of providing a forum for discussion of the current problems with the state-of-the-art and allowing a focusing of research effort which was not previously present in the research community.

As we previously mentioned, in addition to the less quantifiable aspects in terms of networking and connections made, there were several prominent concrete outcomes of the Dagstuhl seminar. The new annotation standard suggested by the two Universal Annotation groups led by Nivre, Petrov and Knight is one strong outcome which will change the basic tools that the statistical machine translation community will have available. The Kirchhoff group is working on a position paper that will help to refocus effort on language modeling for morphologically rich languages, which will have an impact not only on machine translation research but also research on speech recognition and other research areas.

Five of the six most prominent researchers in machine translation in Germany were able to attend the Dagstuhl seminar, and while there have decided to launch a new research program in translating spoken language in an educational context, with a particular focus on translation to German (a morphologically rich language), by submitting a Paketantrag to the DFG. The work will be carried out with a view toward creating a DFG Schwerpunktprogramm focusing on Natural Language Processing for German after the successful completion of the work in the Paketantrag. The researchers are Fraser, van Genabith, Ney, Riezler, Uszkoreit, and they are joined by Alex Waibel (who was invited to the seminar but unable to attend due to scheduling conflicts). This new funding effort would not have been possible without the possibility to meet at Dagstuhl several times to find common ground and determine an overall strategy.

In short, we were very happy with the discussions, work and impact of the Dagstuhl seminar on translation to morphologically rich languages. We plan to apply to hold a second meeting at Dagstuhl in the summer of 2016 on the same topic.

Finally, we would like to once again thank the staff of Dagstuhl for facilitating these unique scientific discussions which we are confident will have a strong impact on future research on the important problem of statistical techniques for translation to morphologically rich languages.

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3 Keynote Talks

3.1 Welcome Note, Challenges, Organizational Issues

Alexander Fraser (LMU München, DE)

While statistical techniques for machine translation have made significant progress in the last 20 years, results for translating to morphologically rich languages are still mixed versus previous generation rule-based systems. In particular the community working on this problem has not yet achieved coherence and as a result resources and tools can be difficult to obtain and results are sometimes not replicable. We briefly discuss these challenges to the community and present the overall organization of the seminar.

3.2 Morphology and Machine Translation

Philipp Koehn (University of Edinburgh, GB)

Many aspects of translation can be best explained on a morphological, syntactic, or semantic level. Having such information available to the translation model allows the direct modeling of these aspects. For instance: reordering at the sentence level is mostly driven by general syntactic principles, local agreement constraints show up in morphology, etc.

Numerous attempts have been made to add richer information to statistical machine translation models. Most of these focus on the pre-processing of the input to the statistical system, or the post-processing of its output.

Rich morphology often poses a challenge to statistical machine translation, since a multitude of word forms derived from the same lemma fragment the data and lead to sparse data problems. If the input language is morphologically richer than the output language, it helps to stem or segment the input in a pre-processing step, before passing it on to the translation system.

One example to illustrate the short-comings of the traditional surface word approach in statistical machine translation is the poor handling of morphology. Each word form is treated as a token in itself. This means that the translation model treats, say, the word house completely independent of the word houses . Any instance of house in the training data does not add any knowledge to the translation of houses . In the extreme case, while the translation of house may be known to the model, the word houses may be unknown and the system will not be able to translate it. While this problem does not show up as strongly in English — due to the very limited morphological inflection in English — it does constitute a significant problem for morphologically rich languages such as Arabic, German, Czech, etc. Thus, it may be preferably to model translation between morphologically rich languages on the level of lemmas, and thus pooling the evidence for different word forms that derive from a common lemma.

The talk will discuss these issues in the handling of morphology, syntax and discourse. The discussion will have a particular focus on morphologically rich languages.

3.3 Morphological Knowledge in Machine Translation

Kristina Toutanova (Microsoft Research – Redmond, US)

Integrating morphological knowledge into statistical machine translation is an important challenge. This talk surveys the state-of-the-art and highlights several important findings. Unsupervised morphology is useful in MT. Pre-processing and redefining the basic units used to translate can be very effective. Factored Models generalize translation rules and incorporate more information locally. Feature-rich models for generation into morphologically rich languages improve quality. New features in standard decoders targeted at agreement and sparsity reduction increase translation quality.

3.4 Explaining Data with Morphology

Kevin Knight (University of Southern California – Marina del Rey, US)

We touch on morphological problems in string-based MT, syntax-based MT, and semantics-based MT. For string-based MT, we review the analysis-transfer-synthesis approach developed at IBM in 1992 by Brown and colleagues. For syntax-based MT, we suggest directions in morpho-syntax models that predict character sequences for morphologically-rich languages. Finally, we introduce an Abstract Meaning Representation for meaning-based translations.

4 Topic-Focused Talks

4.1 Modeling morphemes vs. modeling words and smoothing with morphemes

Chris Dyer (Carnegie Mellon University, US)

The talk argues for using a dual mechanism for modeling morphology. Arguments are drawn from both the psycholinguistic literature and from the state of the art natural language models for language modeling, word alignment and translation. The main argument presented in the talk is that frequent phenomena should be memorized (without generalization, which is computationally expensive), while less frequent phenomena (e.g., the plural of an infrequent noun), should be modeled using rules, resulting in high coverage. We propose the usage of hierarchical models to achieve this, and discuss possibilities for the lexicon representation.

4.2 Modeling Morphology in SMT: Arabic as Example

Nizar Habash (Columbia University, US)

We present some of the challenges in modeling morphology in statistical machine translation (SMT) using Arabic, a morphologically rich language. We discuss features of Arabic orthography, morphology, and morphosyntactic agreement to highlight the need for deep morphological representations in SMT.

4.3 Finding the Best Spot for Morphological Explosion

Jan Hajič (Charles University – Prague, CZ) and Ondrej Bojar (Charles University – Prague, CZ)

How should inflection (e.g., case) prediction be integrated into the decoder? We propose a discussion focusing on different ways to model inflection in the translation model and integrate this model in decoding, rather than using pre- and post-processing techniques. The slides focus on successes and failures of English to Czech MT.

4.4 Language Modeling for Morphologically Rich Languages

Katrin Kirchhoff (University of Washington – Seattle, US)

This talk will survey the state-of-the-art in language modeling for morphologically rich languages, particularly as applied to statistical machine translation. There is little previous work on language modeling for morphologically rich languages in statistical machine translation. There has been no systematic comparison of models. Many models simply haven't been tried yet. In work that has been tried, a better evaluation environment is needed, and in particular evaluation should just focus on the language models.

4.5 Towards a Universal Grammar for NLP?

Joakim Nivre (Uppsala University, SE) and Slav Petrov (Google – New York, US)

There have been several recent initiatives in the parsing community to build treebanks with annotation that is consistent across typologically different languages. Are these resources relevant for machine translation? What needs to be added to make them (more) useful? We propose to come up with a proposal useful for a variety of purposes, including: studying

the way languages encode information, developing better models for translation, generation, parsing, making integration with other analysis and into end-applications easier, supporting cross-linguistic comparison and evaluation, and facilitating annotation of new languages.

4.6 Synthetic Training Data

Joerg Tiedemann (Uppsala University, SE)

Synthetic training data and pivot languages can be used to overcome data sparseness when translating from and to morphologically rich languages. This talk will outline already studied approaches and propose new lines of work.

4.7 (Mostly) Unsupervised Induction of Morphology for SMT

Sami Virpioja (Aalto University, FI)

We present a survey of unsupervised induction of morphology for SMT. We then describe Allomorfessor, which extends the unsupervised morpheme segmentation method Morfessor to account for the linguistic phenomenon of allomorphy, where one morpheme has several different surface forms. The method discovers common base forms for allomorphs from an unannotated corpus by finding small modifications, called mutations, for them.

4.8 Discourse and semantics in SMT, with attention to MRLs

Bonnie Webber (University of Edinburgh, GB)

Aspects of semantic meaning and their discourse-licensed encoding in sentences can make a difference to accurate, fluent translation. Handling these aspects poses challenges to MT, especially when translating into MRLs.

Negation is one such aspect: It can be realized as a separate token, or as a morpheme attached to some root, or as an element that is itself inflected with additional information. Key to its meaning is its scope (the part of a sentence whose meaning is negated). Negation related errors in MT include: incorrectly dropping negation, incorrectly duplicating negation, and inserting negation where it will have the wrong scope.

Aspects of meaning associated with discourse itself are referring forms, semantic and pragmatic relations between sentences (and/or clauses) and information structure. Problematic for MT is the fact that these can appear in highly reduced forms (even zero) because they are obvious from the discourse context. Yet languages differ in what has to be realized explicitly, and human translators may differ in what they choose to make explicit as either lexical items, morphology or both. Dealing with information that is explicit in one language (or one half of a training pair), while implicit in the other is a particular challenge for MT.

4.9 Syntactic SMT for Morphologically Rich Languages

Phil Williams (University of Edinburgh, GB) and Philipp Koehn (University of Edinburgh, GB)

Languages with rich inflectional morphology pose a difficult challenge for statistical machine translation. To address the problem of morphologically inconsistent output, we add unification-based constraints to the target-side of a string-to-tree model. By integrating constraint evaluation into the decoding process, implausible hypotheses can be penalised or filtered out during search. We use a simple heuristic process to extract agreement constraints for German and test our approach on an English-German system trained on WMT data, achieving a small improvement in translation accuracy.

5 Working Groups

5.1 Modeling Inflectional Morphology in Statistical MT Targeting Morphologically Rich Languages

Nizar Habash (Columbia University, US)

The sparsity induced by target-language (TL) inflectional morphology is a fundamental challenge when translating to morphologically rich languages (MRLs). This presentation consists of three parts. First, we present a high level analysis of the various sources of TL inflectional morphology when translating from a variety of poor to MRLs. The presented analysis is supported with examples from a variety of language pairs. Second, we present a unifying description of some of the most commonly used techniques in the field for modeling morphology in statistical machine translation. We observe that one of the most elegant techniques for modeling translation of morphology has a problem with its very large search space. Much of the research on this topic is about strategies for pruning the size of the search space. Finally, we present some general insights and specific suggestions for further research directions. In particular, we think the direction of conditioning inflectional modeling using source and target language features during decoding is likely to address some of the limitations of the current state of the art.

5.2 Language Modeling

Katrin Kirchhoff (University of Washington – Seattle, US)

Our goal is to determine the state of the art in language modeling for SMT or MRLs. Which approaches have been tried? For which languages? Which ones work best? What are open issues/problems to be solved, in terms of modeling approaches, evaluation, resources (training

data)? We have compiled a bibliography of relevant papers on language modeling for MRLs. This will be made public on the Wiki. We discussed in detail those approaches actually used in SMT. We identified gaps/interesting problems. Finally, as a group we are writing a position paper which discusses previous and current research and proposes new directions which should be addressed.

5.3 Semantics and SMT

Kevin Knight (University of Southern California – Marina del Rey, US)

The Semantics and morphology group created a large number of potential questions to pursue, then discussed three of these questions in depth. The questions were: (1) How can we align strings and Abstract Meaning Representations at the token level, (2) How can semantic role labeling and other semantic features improve statistical machine translation, and (3) How can we use powerful syntax translation models to align bilingual text?

5.4 Differences Between Dependency Parses and AMR

Kevin Knight (University of Southern California – Marina del Rey, US)

We discuss some differences between dependencies and Abstract Meaning Representation. The talk will focus on examples motivating the need for a representation beyond dependencies, and introduce the aspects of Abstract Meaning Representation which dependencies cannot model.

5.5 Universal Annotation

Joakim Nivre (Uppsala University, SE)

We propose a scheme for universal annotation useful for morphologically rich languages, based on dependencies with functional leaves. It involves two stages of tokenization/segmentation and a dual annotation of these levels. It handles rich morphology: tags, features and lemmas. By working with two levels of annotation we are able to obtain the power of preprocessing approaches without losing information.

5.6 Unsupervised Morphology

Sami Virpioja (Aalto University, FI)

The challenge we have addressed in this group was to go beyond current approaches which view unsupervised morphology as inducing only a segmentation. In particular, we discussed tailoring unsupervised morphological analysis for MT and alignment. We also discussed new approaches to morphologically aware evalation and proposed a new model incorporating both segmentation and morphology.

5.7 Discourse

Bonnie Webber (University of Edinburgh, GB)

We discussed important issues of discourse with respect to translation. Our discussion was driven by this set of questions:

1. For ensuring register-level consistency in target texts, what is known about register and morphology, register and the lexicon, register and syntax?
2. What aspects of sentences need to persist throughout a discourse (to permit translation)?
3. What aspects of discourse are encoded in morphology?
4. How is scope encoded in non-configurational languages?
5. What are good test sets to use for evaluating aspects of semantics and discourse in translation?
6. What sort of "morphological divergences" occur across languages that express the same features overtly?
7. What aspects of semantics are required to be overt in some languages but not in others? (eg., evidentiality?)
8. What aspects of multiclause (discourse) relations have been captured with syntactic transformations?
9. How to choose articles (eg., def vs indef vs generic) when you have to generate them?
10. How to tackle decoding problem when you have discourse-wide features?
11. If you have consistency, what is the consistency over?

We created a record of our discussion in the Wiki together with a list of papers and data resources for further discussion.

5.8 Syntactic SMT

Phil Williams (University of Edinburgh, GB)

Our group attacked the following goals. We documented the easy win scenarios given the ability to enforce agreement with a focus on linguistic phenomena in languages other than

German. We focused on inflectional languages (e.g. Czech, Russian, Scandinavian and Romance languages) in this discussion. To begin our work, we documented the absolute essentials of morphosyntax in our Wiki page. After carrying out the main discussion, we discussed a number of more difficult problems we expect to encounter with highly-morphological target languages.

5.9 MT Evaluation and Morphologically Rich Languages

Dekai Wu (HKUST – Hong Kong, HK) and Alon Lavie (Carnegie Mellon University, US)

The most commonly used MT evaluation metrics to date, both human and automatic, have done little to address the issues in morphologically rich languages. Both inflectional morphology (as found in languages such as German, Arabic, Finnish, or Czech) and derivational morphology / compounding (as found in all languages but even more acutely problematic in languages such as Chinese, Finnish, or Turkish) cause simple n-gram oriented metrics to significantly underestimate translation accuracy. These issues impact SMT training and tuning when automatic metrics are used as the objective functions. Emerging work on MT evaluation metrics, incorporating explicit morphological components as in METEOR, and/or explicit semantic parsing components as in MEANT, represent strategies to abstract away from surface form n-grams so as to better handle morphological variation. We discuss and analyze key open questions, leading to a roadmap for research to address the deficiencies of MT evaluation metrics for morphologically rich languages.

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Report from Dagstuhl Seminar 14062

The Pacemaker Challenge: Developing Certifiable Medical Devices

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Abstract

This report documents the program and the outcomes of Dagstuhl Seminar 14062 "The Pacemaker Challenge: Developing Certifiable Medical Devices". The aim of the seminar was to bring together leading researchers and industrial partners of this field; the seminary ended up with 24 participants from 8 countries: Canada, Denmark, France, The Unites States, Germany, United Kingdom, Brazil. Through a series of presentations, discussions, and working group meetings, the seminar attempted to get a general view of the field of medical devices and certification issues through the pacemaker challenge. The seminar brought together, on the one hand, researchers from the different notations and various tools. The main outcome of the seminar is the exchange of information between different groups and the project of a book.

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1 Executive Summary

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Pacemakers are typical examples of those medical devices, like insulin pumps, that help save lives when they operate correctly and safely, but may cause grievous harm when they fail. State-of-the art safety standards like IEC 61508 highly recommend (semi-)formal methods for the specification, design, and development of those devices. The Pacemaker Formal Methods Challenge, the first challenge issued by the North American Software Certification Consortium, is hosted by the Software Quality Research Lab at McMaster University, Canada. The challenge is based on a pacemaker specification offered by Boston Scientific, and is part of the verification Grand Challenges which is an international, long-term research programme that seeks to create a substantial and useful body of code that has been verified to the highest standards of rigour and accuracy. The Pacemaker case-study attracted substantial participation during different events in the research community such as workshops at FM2008, FM2009, FHIES 2011, FHIES 2012 and the student competition at ICSE2009 (SCORE).

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Currently there are more than 10 world-class research institutes and universities that take part in the challenge, and are using different approaches. Today, there is a wide range of approaches in the formal methods community to specify and develop high integrity systems. Many of these formal approaches do not work well on industrial level applications, and so the state of the practice is remarkably deficient, even in the case of systems that require certification according to the highest safety levels. The purpose of this five days seminar was to bring together researchers, regulators, as well as practitioners in the medical field to discuss and compare different approaches for the development of certifiable medical software, and further the state of practice. Listed below are research topics related to development of medical software to be covered in the seminar:

- Certification: How can formal methods help in the process of certification of embedded medical software? What standards are in current use and in what measure do they cover model based development? How do we address safety, security and privacy now that these implantable devices are equipped with Wi-Fi, Bluetooth and other wireless networking technologies? How do unspecified environmental assumptions affect the final product?
- Model-based Development: How can established methods for model based development help the building of implantable medical devices? What kind of models (e.g. controlled biological process, hardware platform, safety function) are needed for designing and certifying safety critical medical systems?
- Medical-domain specific aspects: What are the most important specific non-functional aspects that need to be considered while developing implantable medical devices? How can biological and medical aspects be integrated in the development process?
- Tooling: What is the current state of the art and practice concerning tools for formal specification that would be useful in the medical device domain?
- Pragmatics: What is the fitness of different methods for transfer into practice? What do we need to do to ensure that the regulators and workforce are adequately informed of methods and tools that are useful/indispensable in this domain?

As major results of this Dagstuhl Seminar, two publications are targeted at all three relevant sectors researchers, regulators and manufacturers.

The first outcome is a comparison of the different approaches to the Pacemaker Challenge, to be available as a Dagstuhl publication. To achieve such a comparison, the organizers have prepared a catalogue of criteria according to which the approaches are compared. This catalogue was available in advance of the seminar, so presenters can provide a rationale for their classification according to the catalogue, and participants can discuss those classifications.

As a further, more formal result, a joint publication most preferably in the form of a book on the use of rigorous methods for the development of software-intensive medical devices with the pacemaker as a common example will be produced, with the organizers and editors, and all invited research groups as co-authors. Commitment to the participation in this publication will be made a prerequisite for participation in the seminar for members of the research groups having participated in the challenge.

2 Table of Contents

3 Overview of Talks

3.1 Validation via Haskell

Andrew Butterfield (Trinity College Dublin, IE)

Joint work of Butterfield, Andrew; O'Cathain, Art
URL https://bitbucket.org/andrewbutterfield/hpacemaker

Validating a complex formal model, in order to show that it captures the intent of the original requirements author, is very important, but can be very difficult. The difficulty is often increased by the obscure nature of the formalism used. Here we discuss an approach to aid validation that involves generating output from the formal model that mimics the presentation used in the original informal documents. We discuss past work in Flash Memory modelling, and then discuss using Haskell as a modelling language applied to the PACEMAKER challenge. We also present results of addressing a challenge made at the seminar to find a bug in the Pacemaker Specification.

3.2 Innovation and Quality Management

Martin Daumer (Trium Analysis Online GmbH, DE)

URL http://www.actibelt.com
URL http://www.thehumanmotioninstitute.org
URL http://www.trium.de

Innovation and quality management should ideally positively influence each other. but there are cases where they seem to pull in opposite directions, in particular in highly regulated fields like medical device development and clinical research. The major effort to explore, validate, document and integrate innovations or even just improvements in existing products may be used as an argument to continue with the status quo, in particular in price sensitive areas. The effort related to the maintainance and continued development of QM systems, the preparation and management of audits is considerable. Important questions are: are currently used QM systems and audit procedures improving the quality of the core processes? What is the evidence that the quality and safety of the products is increasing? What are the best procedures and structures to allow for a partnership between innovation and quality management? We describe and discuss case studies and solutions from ongoing developments related to the introduction of mobile accelerometry in clinical trials and clinical practice.

3.3 Design Space Exploration through Co-modelling and Co-Simulation: the Pacemaker Challenge

John S. Fitzgerald (Newcastle University, GB)

We have presented a study demonstrating that collaborative modelling and co-simulation can be used to explore design alternatives in the context of the pacemaker challenge problem.

Specifically, we showed the use of The Vienna Development Method (VDM) as a discrete-event formalism modelling the controller, coupled to a continuous-time model of the leads and heart environment represented in 20-sim. The modelling technology is formal but readily accessible, using pre-existing formal notations that each have their own simulator support. Our co-simulation tool links the two simulators, implementing a reconciled operational semantics, managing the passage of data, events, and the sometimes delicate progression of time between the two sides. Previous work on modelling the pacemaker controller in VDM concentrated only on the discrete-event model of behaviour, and on the generation of simulation traces using a coarse environment model. Our work reported here provided a stronger environment model built up from primitives. The possibilities for the exploration of design alternatives through co-simulation were illustrated by examining the requirement to change from synchronous to asynchronous pacing modes in the presence of noise (e.g. DDD to DOO, and AAI to AOO). A 20-sim heart model was constructed that allowed the modelling of alternative lead placements, and on the VDM side we modelled the normal controller operation, plus the mode change on noise detection. A feature of this approach is the ability in one model to observe effects of cyber or physical design decisions on system behaviour as a whole. For example, we have only examined one noise detection solution, largely in software and hence modelled in the discrete-event formalism. However, other methods such as filtering (modelled in the continuous time notation) can equally well be explored in exactly the same framework.

3.4 Formal Safety Analysis and Verification of a Family of Cardiac Pacemakers Using SCADE

Michaela Huhn (TU Clausthal, DE)

Joint work of Huhn, Michaela; Sara Bessling
Main reference M. Huhn, S. Bessling, "Enhancing product line development by safety requirements and verification," in Proc. of the 2nd Int'l Symp. on Foundations of Health Information Engineering and Systems (FHIES'12), LNCS, Vol. 7789, pp. 37–54, Springer, 2013.
URL http://dx.doi.org/10.1007/978-3-642-39088-3_3

We investigate the feature-oriented model-based development of a family of pacemakers in a formally founded modeling framework that fosters formal verification. We show how to formalize the findings of a safety analysis uniformly. Then we employ model checking for safety assurance and prove a number of functional properties to hold on the individual pacemaker variants. We extend the SCADE development framework, a tool suite for safety-critical systems based on a formally founded synchronous modeling language, by a transformational approach to product line design: As features are the main concept of functional decomposition in the product line approach, features also direct the safety analysis and the specification of system-level safety requirements: Hence, safety (design) constraints are allocated to features. VIATRA is employed to implement product resolution, i.e. the model graph transformation generating the individual products according the selected feature set. The behavior of components assocoated with a feature is formally modeled inScade language. System Theoretic Process Analysis (STPA) by N. Leveson is applied for hazard analysis. The findings, possible deviations and faults, but also the derived safety constraints are added to the models. Then formal verification techniques are employed in order to prove that the safety constraints are satisfied and thesystem level hazards are prevented. Functional safety

is proven using SCADE Design Verifier. The combination of feature-oriented decomposition and STPA leads to a fine-grained safety analysis and is capable of uncovering unwanted interactions. The case study shows that formal methods and tools are ready for use within the software development of medium sized real-world dependable products.

3.5 Model-based Design of Pacemaker Software with Closed-loop Evaluation

Zhihao Jiang (University of Pennsylvania, US)

Joint work of Jiang, Zhihao; Pajic, Miroslav; Alur, Rajeev; Mangharam, Rahul
Main reference Z. Jiang, M. Pajic, R. Alur, R. Mangharam, "Closed-loop verification of medical devices with model abstraction and refinement," International Journal on Software Tools for Technology Transfer, Volume 16, Issue 2, pp. 191–213, April 2014.
URL http://dx.doi.org/10.1007/s10009-013-0289-7

Increasing complexity of the pacemaker software leads to increasing number of potential safety issues. The state-of-the-art pacemaker evaluation is based on open-loop testing which is not able to capture all the closed-loop behaviors. Furthermore, there is no formal techniques used during the development process to maintain the traceability of the requirements. To address these problems, we developed a model-based design framework for pacemaker software which can translate a verified pacemaker model to verified pacemaker implementation. A heart model is designed at different development stages (verification ⇒ simulation ⇒ testing) to evaluate the pacemaker safety/efficacy in closed-loop. The framework improves the confidence of the safety/efficacy of a pacemaker design which reduces the design efforts and increases the speed of certification. For more info please visit our website: http://medcps.org

3.6 Towards product-based certification of medical devices

Soeren Kemmann (Fraunhofer IESE – Kaiserslautern, DE)

The certification of medical devices is currently done by checking the compliance of the manufacturer to international safety standards. Those safety standards however do not focus on the medical device as a product and the irinherent product qualities, but are focused on prescribing rigorous processes. There is however (to the best knowledge of the author) no evidence that good processes lead to good products. Another issue regarding these process based standards is that sometimes innovations or innovative products to not fit into the prescribed process and its therefore hard to certify them. The usual case isthat first the standard is adapted/renewed and afterwards those products can be put on the market. This hinders to a large extend innovations. Another philosophy is that one should focus on the product and make the product safe, This of course requires argumentations and evidences of the product or itsdevelopment to show that the desired system property, safety, is fulfilled. There are already approaches addressing this, such as assurance cases, but they lack of guidelines and support for the manufacturer. We therefore propose an approach focused on arguing product qualities, butincluding guidance for the manufacturer how to develop those.

3.7 The Meaning of PACEMAKER: Formal Semantics for Chapter 5 of PACEMAKER System Specification with BLESS

Brian Larson (Kansas State University, US)

Joint work of Larson, Brian; Hatcliff, John; Chalin, Patrice
Main reference BLESS: Formal Specification and Verification of Behaviors for Embedded Systems with Software, Brian R. Larson, Patrice Chalin, and John Hatcliff, NASA Formal Methods, 2013.
URL https://bless.santoslab.org/

During the editing process at Boston Scientific to transform a company-confidential system specification into the publicly-released *PACEMAKER System Specification* this contributor sought temporal logics that could define pacemaker timing. Having surveyed dozens of temporal logics, finding none suitable for the pacemaker timing of PACEMAKER, this contributor tried extending first-order predicate calculus with simple temporal operators. All features of PACEMAKER were described declaratively using Assertions; the document text was edited to be transliterations of the Assertions into natural language. A very simple extension of first-order predicate calculus was found to be sufficient to define all pacing behavior in PACEMAKER:@ fixes the moment when its predicate is evaluated.[1]

For predicate q and time s, $(q@s \equiv qs)$ The fundamental safety property of PACEMAKER is Lower Rate Limit (LRL).

```
<<LRL:x: --Lower Rate Limit exists t:T --there was a moment in x-1..x
--within the previous LRL interval that (n@t or p@t) >>
--with a pace or non-refractory sense
```

defines a predicate `LRL` applied to parameter `x`, where `n` and `p` are names of ports, and that`n@t` means and event occurred on port `n` at time`t` and `p@t` means and event occurred on port `p`at time `t`. The most recent heartbeat occurred within the last LRL interval can be expressed as `<<LRL(now)>>`, where `now`refers to the present instant.*All* functions in Chapter 5 of PACEMAKER were defined using this temporallogic, and individually compared with the natural language text. No other temporal logic known to seminar participants could similarly capture the semantics of PACEMAKER.

3.8 The Pacemaker Challenge Hardware 2.0

Mark Lawford (McMaster University – Hamilton, CA)

Joint work of Lawford, Mark; Larson, Brian; Wassyng, Alan

We provide some background on the Pacemaker Challenge Hardware reference platform and make the case that it is important for people working on Certification to take into consideration the complete system, including hardware. To date however, Formal Methods researchers have tended to "cherry pick" the problems that show their method in the best light, typically at the requirements level, while embedded systems students have focused on working code that lacks formal specifications. We describe some of the limitation with the

[1] added `q^i` for periodic threads post Spec

current PIC18 based platform that have led to the current situation, namely that it used an RS-232 serial interface and separate power supply rather than a USB connection, required a separate device programmer, had limited open source C compiler support, and required a significant amount of low level driver code to make the system work.We discuss how these limitations can be addressed by redesigning the hardware. Alternatives hardware platforms are analysed and then details on a proposed new Pacemaker Challenge Hardware Reference platform are provided.

3.9 Architecture Centric Modeling – Models of Views, Refinement and Integration

Zhiming Liu (Birmingham City University, GB)

Joint work of Liu, Zhiming; He, Jifeng; Li, Xiaoshan; Stolz, Volker; Zhan, Naijun; Dong, Ruzhen; Ke, Wei; Faber, Johannes
Main reference R. Dong, J. Faber, W. Ke, Z. Liu, "rCOS: Defining Meanings of Component-Based Software Architectures," in Proc. of the International Training School on Software Engineering held at ICTAC 2013, Advanced Lectures on "Unifying Theories of Programming and Formal Engineering Methods," LNCS, Vol. 8050, pp. 1-66, Springer, 2013.
URL http://dx.doi.org/10.1007/978-3-642-39721-9_1

Engineering a complex application software system requires models of different aspects of the system architecture, and different view points of different users. These applications include such as web applications for the cloud, internet of things and cyber-physical systems (CPS). Our presentation at the seminar discusses how models for separation of concerns, refinement, and integration are treated in the rigorous model driven development method. We argue for the need of a unified semantic theory that to enable the consistency use of different logics, techniques and tools for requirements analysis, design, verification and validation. The theory and techniques support the development of tools and methods of software design too. In relation to the case study of the Pacemaker Challenge, we discuss differences between system requirements and software requirements. We in particular show how models system architecture in terms of components and their interfaces can be used to formulate Parnas' Four Variable Model to define the boundary of environment and the software program. The refinement relation is then applied to develop the models of the environment, i.e. the heart, and the Pacemaker control program at different levels of abstraction. We also used the case study to demonstrate the need of a unified semantic theory to support the use of different logics is prosed, such Duration Calculus (DC), LTL with bounded temporal operators, and clocked based logics used with timed automata. The proposed approach is based on our ongoing research of the rCOS Model-Driven Method and the transformational approach to design and verification of real-time and fault-tolerant systems.

3.10 The Pacemaker Challenge – Criteria Catalogue – Development of Medical Device Software System using Event B

Dominique Méry (LORIA – Nancy, FR)

Joint work of Méry, Dominique; Singh, Neeraj Kumar
URL http://eb2all.loria.fr

We summarize our contribution to the Pacemaker Challenge including a list of references of our results and works. Our goal is to integrate the use of formal techniques for designing the software for medical systems. This integrationmay help to identify the possible flaws in the existing system, increasing the quality, and provide some safety assurances to certification standards considering verification and validation approach. We have both academia and practitioners as the target readers. During our work, we met some industrial people (Sorin, Paris); they were looking for some solutions, which exactly match to our developed solution. On the other hand, our developed solutions can also help to students to understand the development of complex systems, like pacemaker. With respect to the technology readiness level of our approach, it may satisfy the TRL4 level (http://www.lbl.gov/dir/assets/docs/TRL%20guide.pdf, page 9).

We spent two yearsto obtain the solution (Event B models) including tools development. In our work, we consider the operating modes of a cardiac pacemaker. Particularly, we verify the pacing and sensing behaviour of cardiac pacemaker including *hysteresis*, and *rate modulation*. We consider the software and the interaction with the physicians. The environment has been partly modelled. We have modelled the biological environment (the heart) for a cardiac pacemaker or ICD. The heart model is based on electrocardiography analysis, which models the heart system at the cellular level. The main objective of this heart model is to provide a biological environment (the heart) for formalizing a closed-loop system (a combined model of a cardiac pacemaker and the heart) to verify the system requirements at an early stage of the system development. Event-B modelling language provides the classical techniques for verifying formal models using refinement mechanism, which is a very powerful feature for developing a formal model progressively. Moreover, Event-B is supported by a very powerful platform Rodin providing a proof obligations generator, editor of models, automatic provers, interactive proof assistant and a tool for animating and model checking models. The Event-B formalism is based on a set-theoretical predicate calculus and structures for organising and expressing models namely contexts for stating static properties over data and machines for expressing transitions or actions called events over state variables. The formalism is rigorous, and it allows to express the safety properties and invariant properties. It is a formalism that supports the correct-by-construction paradigm using the refinement or simulation as a mechanism for structuring the development. The notation is simple but the development of models requires both skills in modelling and in proving. Discrete maths are very difficult notions but Event B is as simple as techniques for developing models in fluid mechanics for instance. These engineers in fluid mechanics are trained in maths and physics and we think that Event B is accessible as long as you play with abstractions. The developed Event B models have been verified and validated using tools of the RODIN platform. Pacing and sensing behaviours of each operating modes under the specified time intervals including features like hysteresis and rate modulation. We ensure safety and invariance properties by construction. We have used both model checker and theorem prover (Rodin) in our work. Engineers can play with the animator and the model checker. They can also discharge many proof obligations as long as they are experts in modelling. The validation is operated through

the use of a plugin relating the animation of the model and a view of the heart. It is called areal-time validation in our approach. For communicating with the physicians and medical experts, we have used Flash animation and programming to animate the proved formal model of Event-B. Moreover, we have also implemented the cardiac operating modes in SCJ (Safety Critical Java), and ECG signal interface in Java for developing the simulation. Synthetic ECG signal is generated for simulation purpose. The pacemaker challenge is a very critical application for illustrating and for improving scientific results and especially the discovery of new waysto structure models in Event B. It helps to state questions relating formal techniques and clinical questions. We got many interactions with scientific and industrial partners related to this topics. It is probably a very good illustration that we are addressing real societal questions even with ethical issues.

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3.11 Modeling Pacemaker with mbeddr

Zaur Molotnikov (fortiss GmbH, DE)

Joint work of Zaur Molotnikov; Daniel Ratiu; Markus Völter; Thomas Böhm
URL http://mbeddr.fortiss.org/

We have presented preliminary results demonstrating the use of language engineering techniques applied to the Pacemaker Challenge. For this we used a combination of mbeddr and CBMC, free and open-source technologies. Our is a part of mbeddr.

We have modelled and functionally verified on the C code level two pacing modes: VVI and DDD. It turns out, that using language engineering technologies and code level verification it is possible to create verified subsystems. The resulting artifact, C code, is all: executable, functionally verified, lightweight, deployable. We validate the latter two by deploying the DDD pacing logics to Adruino platform, and performing testing, which shows adequate performance and behavior.

The future work is to be done, however, before the method can be applied in practice. The verification is to be characterized, as code transformation and CBMC might introduce problems in it. The model-checking-based process is made more applicable with language-engineering, but additional work is still to be done to ensure scalability to bigger systems/more subsystems of a pacemaker.

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3.12 Model-Based Design and Medical Devices

Pieter J. Mosterman (The MathWorks Inc. – Natick, US)

Joint work of Mosterman, Pieter J.; Zander, Justyna; Denckla, Ben; Hamon, Gregoire; Ghidella, Jason; Prabhu; Erkkinen, Tom; Schieferdecker, Ina
Main reference P. J. Mosterman, J. Zander, G. Hamon, B. Denckla, "A computational model of time for stiff hybrid systems applied to control synthesis," Control Engineering Practice, Vol. 20, Issue 1, pp. 2–13, January 2012.
URL http://dx.doi.org/10.1016/j.conengprac.2011.04.013

Model-Based Design has been successfully used in Aerospace and Automotive domains. Recently it is gaining interest from the medical devices community. Based on a high-level design process, this presentation illustrates where computational models and tools help improve design and test. Furthermore, it is argued that using computational models as deliverables between design stages requires formalizing the computational semantics of numerical algorithms in an execution engine.

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3.13 The Pacemaker Grand Challenge – From Specification to Hardware

Marcel Oliveira (Federal University of Rio Grande do Norte, BR)

Main reference A. O. Gomes, M. V. M. Oliveira, "Formal Development of a Cardiac Pacemaker: From Specification to Code," in Proc. of the 13th Brazilian Symposium on Formal Methods (SBMF'10), LNCS, Vol. 6527, pp. 210–225, Springer, 2010.

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As a contribution to the International Grand Challenge project on Verified Software, which aimed to stimulate the creation of newtheories and tools to be applied on industrial-scale problems, we presented a formal model of the pulse generator (PG) of a cardiac pacemaker using the Z notation. Later on, we translated this specification into the Perfect Developer language, from which we automatically generated C# executable code. More recently, we have targeted the Arduino Micro Controller Board. For that, using Perfect Developer, we automatically generated C++ executable code, with which, unfortunately, Arduino could not cope. With some changes in the generated code, we were able to execute the PG in the Arduino board. This execution, however, presented further problems. This talk seeks to promote a discussion on the validity of the approach as well as on the possible solution to overcome our current problems with the running prototype.

3.14 Testing and Operational Evidence of Safety-Critical Software: when is it enough for Certification?

Francesca Saglietti (Universität Erlangen-Nürnberg, DE)

Joint work of Saglietti, Francesca; Lill, Raimar; Meitner, Matthias; Oster, Norbert; Pinte, Florin; Söhnlein, Sven

The talk addressed the importance of explicit test coverage demands for safety-critical software, where the term "coverage" can be taken to refer to the degree to which the behavioral multiplicity or the usage profile are captured during testing. The presentation started by highlighting potential limitations of software verification and validation processes

relying on purely formal techniques and stressed the importance of complementing such approaches by extensive and measurable testing and operational evidence. After a comparison of coverage demands posed by different safety standards, the talk focused on research work supporting structural testing by automatizing as far as possible the underlying test data generation process. The use of genetic algorithms revealed to offer useful heuristics for the solution of multi-objective optimization problems involving both the maximization of testing coverage and the minimization of testing effort. Different testing environments were reported to have been automatically optimized in the light of these conflicting targets: among them are the integration testing of synchronously interacting software components as well as the interoperation testing of autonomously cooperating robotic entities.The final part of the talk was devoted to the quantitative evaluation of operational evidence gained with proven-in-use software. In a real-world automotive application involving a software-based gearbox controller, statistical sampling theory revealed to provide a practicable instrument for the extraction of conservative reliability estimates. In order to avoid functionally incomplete operational experience, structural and reliability testing targets were combined into a novel testing strategy aiming at the generation of statistically independent and operationally representative test scenarios capable of covering the data flow induced by component invocations.

3.15 Model-Based Engineering for Medical Device Software

Bernhard Schaetz (fortiss GmbH – München, DE)

Joint work of Schaetz, Bernhard; Ratiu, Daniel; Gareis, Stephanie; Chen, Wenwen

Models can contribute to a high-quality development process of embedded software by

1. providing dedicated and concise views of the systems and environment under consideration
2. enable analysis techniques to front-load quality assurance
3. enable synthesis techniques to automate development steps and support design-space exploration.

To assess the usefulness of the model-based approach for medical software, several techniques recommended in standards for safety-critical software-intensive systems (e.g., IEB 61508) were applied to the pacemaker challenge using the AutoFocus3 (AF3) development approach and tool. AF3 provides dedicated views (e.g., textual requirements, template-based property descriptions, component-based system specification, platform description), strong analysis (e.g., non-determinism analysis, verification of properties), and synthesis techniques (e.g., test case generation, deployment generation). Using these techniques, a complete development process was carried out, starting from the textual requirements based on the Boston Scientific Specification and leading to a running implementation on the MSCert prototyping hardware combined with a implementation of the physical heart model on a PIC18F5420 microprocessor. For all the produced artifacts – requirements specification, pacemaker system and software design, logical context/heart model, pacemaker implementation, physical heart model implementation – and performed steps – requirements structuring and formalization, conformance verification, soundness analysis, MiL and HiL verification, requirements-based testing, conformance testing, code generation and deployment of pacemaker software and heart model – we demonstrate how these are supported by or automated by the AF3 approach and how this contributes to a development process according to IEC 61204.

3.16 Development of Medical Device Software Systems

Neeraj Kumar Singh (McMaster University – Hamilton, CA)

Joint work of Singh, Neeraj Kumar; Méry, Dominique

Formal techniques are not well integrated in the software development life-cycle of medical device software systems. We propose a development life-cycle to develop the medical systems using formal techniques from requirements analysis to code generation. In this context, we have provided a chain of tools support to realize the rigorous process development considering the safety assessment approaches. Moreover, we also address the necessity of an environment model and real-time animator to bridge a gap between the stakeholders. Our approach is to design a system in a progressive fashion using refinements. Each refinement level introduces the new concrete behaviours considering some safety properties to make sure the correctness of desired functional behaviours. To evaluate our proposed life-cycle and associated tools, we use the Grand Challenge cardiac pacemaker.

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3.17 Grand Challenge Problems for Education

Alan Wassyng (McMaster University – Hamilton, CA)

Joint work of Wassyng, Alan; Lawford, Mark

This talk provides a brief retrospect of the PACEMAKER Grand Challenge, anopinion as to how successful it has been, and how it has been used for teaching at McMaster University. The primary goal of the talk is to suggest that the PACEMAKER Challenge and other such future challenges can be used as influentialcase studies in education.

3.18 Timing Analysis of Pacemakers

Reinhard Wilhelm (Universität des Saarlandes, DE)

Modern high-performance processors introduce a large variability in the execution time of machine instructions. Determining worst-case program execution times (WCETs) is therefore a difficult problem. I present a solution to this problem using static program analysis incorporating an abstract model of the architecture. Such a static analysis of a program computes an invariant at each program point. This invariant describes all execution states that the HW may be in when program execution reaches thisprogram point. The invariant can be used to determine a reliable and precise upper bound on the execution

time of the instruction at this program point and on the execution time of the containing basic block. Based on these bound a worst-case path is determined through the basic-block graph of the program. This approach and tools based on it are in routing use in the embedded-systems industry. They have been accepted and used for certification of several time-critical subsystems in modern airplanes. It seems that this technology has not a very high relevance for pacemakers since the real-time requirements are rather modest and the amount of computation is also quite limited.

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4 Working Groups and Panel Discussions

We have reported the summary of a planned book that was emerging during our seminar. Works will go ahead after the seminar. By the end of the seminar, we obtain the following sketch for this book. The summary of the book is resulting from panel discussions and planned working groups attached to each chapter of the book. We are skectchig chapters planned for the book and we warn readers that some chapters are not yet completely defined.

1. Introduction: *what's it about? emphasis on evidence for certification, aimed at regulators, acceptable risk, not "no risk", focus on critical systems (Class III), Common Terminology/Glossary*
2. Pacemaker Challenge: *This section will recall the Pacemaker Challenge and outcomes.*
3. Certification Overview: *certification goal, Safety & Efficacy, Assumptions and problem statements/Objectives and Requirements (everywhere)*
4. Current Practice: *process based, good historical reasons for this, approaches to risk/hazard analysis, no evidence it works*
5. Process and Product: *the argument for this, reify safety/efficacy into product qualities/properties, certification checks EVIDENCE, FMEA – what's best for software?, EVIDENCE, how to cover everything? how to avoid systemic error?*
6. Rigorous Methods for Development of Safety-Critical Systems: *Summary on fomal methods related to certification and medical devices*
7. Producing Product Qualities and Evidence: *confidence vs evidence, benefit of mathematical rigour, v. high confidence in domain of applicability, Evidence Classes vs Development Phases, applicability conditions for evidence classes in each phase, Remember: focus is on CERTIFICATION, processes for devpt for certification vs. processes for certification*
8. Tools for Development of Safety-Critical Systems: *Introduction (not an overview; Types of tools (primarily model-based with simulation, model-checking, theorem proving etc. but also the operating system, compilers etc.); Roles of different involved stakeholders (developer, regulator, end user,) (different stakeholders have different issues, technical, business) (used for development of systems (not for certification authority in itself although requirements traceability may be useful); tool chain considerations (semantically connected tools); tools for producing models for different viewpoints (using separation of concerns and abstraction) of key parts of a system with a specific purpose of analysis is recommended (Model stuff, produce artifacts that can be used to gain confidence in the safety and correctness of the system, engineering reasoning between such dedicated models and the claim produced mush be provided; qualification/validation of tools (including what is done*

in other application domains) independent analysis tools that can increase confidence could be used with advantage even without certification/validated (In particular it is valuable to have multiple independent tools analysing the same aspects in order to increase likelihood of correctness; The state-of-the-art analysis tools here shall be used to incorporate safety and correctness of medical system); Concluding Remarks

9. New Roles for Regulators and Standards: *acceptable risk, not "no risk"; standards should focus on which qualities/properties to assure; state required levels of confidence; competency; certification should check if acceptable confidence; level attained; required knowledge: (i) for regulator; (ii) for developers.*
10. Conclusion

A shared collaborative space is provided to potential contributors among the participants of the seminar.

5 Conclusions

It became obvious during this seminar that challenge problems like the PACEMAKER Challenge are invaluable for stimulating research and furthering the state of that research, facilitating collaborations, providing a focus for application of theory to a specific, practical problem, and for high quality case study material that could be used in education. A few lessons emerged for future such Grand Challenges: 1) A hardware platform that can be used uniformly by all collaborators is a real advantage. Even with the limitations of the PACEMAKER reference hardware, having that platform available (at reasonable cost) contributed to the success in getting so many groups to participate in the Challenge; 2) We need better defined rules for such challenges. That way we will be able to make better comparisons between competing approaches; 3) We need to be able to plan and support workshops and seminars for participants actively engaged in the Challenge (Dagstuhl is an incredibly effective vehicle for this kind of meeting); 4) Special issue publications are necessary to really disseminate the work. The upcoming book arising out of this Dagstuhl Seminar is a good example. 5) There should be a number of target audiences for each Challenge, and publications can target one or a number of those audiences. The fact that the upcoming book from this Seminar targets Medical Device Regulators, is an enterprising move. It has the potential to make a difference in a very practical way.

In conclusion, the presentations at this Dagstuhl Seminar, focused on improving the quality (safety, security and dependability) of medical device software, specifically the Pacemaker, were of very high quality. Even more useful to the community was the in-depth and extensive discussion that took place. The upcoming book is now of immediate concern, and the first milestone for examining drafts and revising direction, if necessary, is due at the end of June 2014.

The organizers wish to thank all the participants for their excellent contributions, and the staff and organizers of Dagstuhl for this wonderful opportunity.

6 Programme

Monday – February 3, 2014

09:00–10:30 Welcome, Overview & Introductions: What we want out of this seminar
10:30–11:00 Coffee
11:00–12:15 Brian Larson – The PACEMAKER Spec
12:15–13:30 Lunch
13:30–14:30 Martin Daumer – Certification affects innovation
14:30–15:30 Gunter Klebes – Quality assurance for certification
15:30–16:00 Coffee
16:00–17:00 Roland Mols answers domain questions
17:00–17:30 Dealing with the medical domain

Tuesday – February 4, 2014

09:00–10:30 Case Study 1: Artur Gomes & Marcel Oliveira
Case Study 2: Dominique Méry & Neeraj Singh
Case Study 3: Zhiaho Jiang
10:30–11:00 Coffee
11:00–12:00 Case Study 4: John Fitzgerald & Peter Gorm Larsen
Case Study 5 Brian Larson
12:00–13:30 Lunch
13:30–15:00 Case Study 6: Markus Völter & Zaur Molotnikov
Case Study 7 Michaela Huhn
Case Study 8 Daniel Ratiu & Bernhard Schätz
15:00–15:45 Discussion on Case Studies
15:45–16:00 Coffee
16:00–16:30 Francesca Saglietti – Testing and Certification
16:30–17:00 Soeren Kemmann – Standards for Medical Software
17:00–17:30 Reinhard Wilhelm – Verification of Non-Functional Aspects

Wednesday – February 5, 2014

09:00–9:30 Pieter Mosterman – Analysis & Design Tools for Medical Devices
09:30–10:00 Andrew Butterfield - Validation
10:00–10:30 Do we need to model the environment?
10:30–11:00 Coffee
11:00–11:30 Mark Lawford – Hardware for Challenge Problems
11:30–12:00 Alan Wassyng – Using Challenge Problems for Teaching
12:00–13:30 Lunch
13:30–21:00 Excursion

Thursday – February 6, 2014

09:00–9:20 Christian Prehofer – medical devices: some observations
09:20–10:30 Elaboration of topics
10:30–11:00 Coffee
11:00–12:00 Prioritization of topics
12:00–13:30 Lunch
13:30–14:30 Declaration of interest: topics & involvement
14:30–15:45 (Q&D) attempt: Topic specific points for elaboration
15:45–16:00 Coffee
16:00–17:30 Discussion on Topic specific points for elaboration

Friday – February 7, 2014

09:00–10:30 Discussion on Topic specific points for elaboration
10:30–11:00 Coffee
11:00–12:00 Summary on the project of book
12:00–13:30 Lunch

Participants

- Andrew Butterfield
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- Martin Daumer
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- John S. Fitzgerald
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- Michaela Huhn
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- Zhihao Jiang
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Report from Dagstuhl Seminar 14071

Graph Modification Problems

Edited by

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Abstract

This report documents the program and the outcomes of Dagstuhl Seminar 14071 "Graph Modification Problems". The seminar was held from February 9 to February 14, 2014. This report contains abstracts for presentations about the recent developments on algorithms and structural results for graph modification problems, as well as related areas. Furthermore, the report contains a summary of open problems in this area of research.

Seminar February 9–14, 2014 – http://www.dagstuhl.de/14071
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1 Executive Summary

Hans L. Bodlaender
Pinar Heggernes
Daniel Lokshtanov

A surprisingly high number of the interesting computational problems arising from theory and applications can be formulated as *graph modification* problems. Here we are given as input a graph G, and the goal is to apply certain operations on G (such as vertex deletions, edge deletions, additions or contractions) in order to obtain a graph H with some particular property. For an example the classical Vertex Cover problem can be formulated as trying to change G into an edgeless graph by performing the minimum possible number of vertex deletions. The Cluster Editing problem is to change G into a disjoint union of cliques with a minimum number of edge deletions or additions. Graph modification problems have been studied quite extensively, and both algorithms for these problems and structural aspects have been thoroughly explored.

Graph modification problems have received a significant amount of attention from the perspective of Parameterized Complexity. In parameterized complexity input comes with a parameter k and the goal is to design *fixed parameter tractable* algorithms, i.e. algorithms with running time $f(k)n^{O(1)}$ for some, hopefully not too fast growing function f. The parameter k can be the size of the solution sought for, or it could be a number describing how structured the input instance is. For an example k could be the *treewidth* of the input graph. Over the last few years, our understanding of the parameterized complexity of graph

modification problems has greatly improved. Fixed parameter tractable algorithms have been found for a number of fundamental graph modification problems. For several problems, surprising new algorithms with *subexponential* ($2^{o(k)}$) dependence on k have been developed.

There is a strong connection between graph modification problems and *graph classes*. A graph class is simply a set of graphs satisfying some common properties. Thus many, if not all, graph modification problems can be phrased as modifying the input graph G by as few operations as possible to make it fit into a particular graph class. There is a large and active Graph Classes research community that primarily investigates how restricting the *input* graph to a particular graph class affects the computational complexity of computational problems. In the setting of graph modification problems we have no restrictions on the input graph, but the problem definitions dictate which graph class the *output* graph should belong to. The main objective of the seminar was to bring together experts within Parameterized Algorithms and experts within Graph Classes to join forces on graph modification problems. We also invited experts from related areas, such as Structural Graph Theory and Bioinformatics. Structural graph theory, in order to learn of the new powerful graph theoretic tools being developed, and hopefully to apply them on graph modification problems. Bioinformatics, in order to better understand the relationship between the idealized models we study and real-world applications of graph algorithms.

The scientific program of the seminar consisted of 21 talks. 4 of these talks were longer (45 or 90 minute) presentations covering some of the most exciting developments on graph modification problems and related areas. We had one long talk for each of the main topics covered by the seminar. On Monday, Marcin and Michał Pilipczuk gave a joint 90 minute talk ("Subexponential parameterized complexity of completion problems") on parameterized algorithms. On Tuesday, Paul Medvedev gave a 45 minute talk ("An introduction to genome assembly and its relation to problems on graphs") showcasing how graph algorithms can be used in Bioinformatics applications. On Wednsday, Kristina Vušković gave a 45 minute presentation ("Weighted Independent Set in bull-free graphs") about how deep structure theorems can be useful in algorithm design, and on Thursday, Andreas Brandstädt gave a presentation ("Clique separator decomposition for a subclass of hole-free graphs") on graph classes. We believe that the invited talks were a good starting point for cross-community collaboration. The remaining talks were 30 or 35 minute presentations on recent research of the participants. We made a point out of having fewer short talks, in order to leave more time for individual discussions and collaboration in groups, as well as for open problem sessions. The idea was to reserve almost all of the time between lunch and dinner for research. This was very well received by the participants. There were 3 fruitful open problem sessions, on Monday, Tuesday and Thursday. Notes on the presented problems can be found in this report.

2 Table of Contents

3 Overview of Talks

3.1 A few things about linear rankwidth

Isolde Adler (Goethe-Universität Frankfurt am Main, DE)

Joint work of Adler, Isolde; Farley, Art; Ganian, Robert; Kante, Mamadou; Kwon, O-joung; Proskurowski, Andrzej

Path-width can be seen as linearized variant of tree-width, and similarly, linear rank-width is the linearized version of rank-width. It is defined like rank-width by restricting the decomposition trees to being caterpillars. It is known that a graph class has bounded linear rank-width if and only if it has bounded linear clique-width. Many problems that are NP-hard in general become tractable on graphs on bounded (linear) rank-width. For instance, this is the case for all problems expressible in MSO_1 (monadic second order logic with quantification over vertex sets only).

While path-width is a well-studies notion, much less is yet known about linear rank-width.

If a graph class has bounded path-width, then it has bounded linear rank-width. The converse is not true: cliques and complete bipartite graphs have linear rank-width 1, but their path-width is unbounded.

Since computing linear rank-width is NP-hard in general, we are interested in finding graph classes that permit an efficient computation of linear rank-width.

In this talk we give a short overview of the state of the art and we present some results on trees and distance-hereditary graphs.

The talk includes results of joint work with Art Farley, Robert Ganian, Mamadou Kante and O-joung Kwon and Andrzej Proskurowski.

3.2 Parameterized complexity of three edge contraction problems with degree constraints

Rémy Belmonte (Kyoto University, JP)

Joint work of Belmonte, Rémy; Golovach, Petr A.; van 't Hof, Pim; Paulusma, Daniël
Main reference R. Belmonte, P. A. Golovach, P. van 't Hof, D. Paulusma, "Parameterized Complexity of Two Edge Contraction Problems with Degree Constraints," in Proc. of the 8th Int'l Symp. on Parameterized and Exact Computation (IPEC'13), LNCS, Vol. 8246, pp. 16–27, Springer, 2013.
URL http://dx.doi.org/10.1007/978-3-319-03898-8_3

For any graph class $\mathcal{H}$, the $\mathcal{H}$-Contraction problem takes as input a graph G and an integer k, and asks whether there exists a graph $H \in \mathcal{H}$ such that G can be modified into H using at most k edge contractions. We study the parameterized complexity of $\mathcal{H}$-Contraction for three different classes $\mathcal{H}$: the class $\mathcal{H}_{\leq d}$ of graphs with maximum degree at most d, the class $\mathcal{H}_{=d}$ of d-regular graphs, and the class of d-degenerate graphs. We completely classify the parameterized complexity of all three problems with respect to the parameters k, d, and $d+k$. Moreover, we show that $\mathcal{H}$-Contraction admits an $O(k)$ vertex kernel on connected graphs when $\mathcal{H} \in \{\mathcal{H}_{\leq 2}, \mathcal{H}_{=2}\}$, while the problem is W[2]-hard when $\mathcal{H}$ is the class of 2-degenerate graphs and hence is expected not to admit a kernel at all. In particular, our results imply that $\mathcal{H}$-Contraction admits a linear vertex kernel when $\mathcal{H}$ is the class of cycles.

3.3 Clique separator decomposition and modular decomposition for some subclasses of odd-hole-free graphs

Andreas Brandstädt (Universität Rostock, DE)

Joint work of Brandstädt, Andreas; Berry, Anne; Giakoumakis, Vassilis; Maffray, Frédéric; Mosca, Raffaele
Main reference A. Brandstädt, V. Giakoumakis, F. Maffray, "Clique separator decomposition of hole-free and diamond-free graphs and algorithmic consequences," Discrete Applied Math. 160 (2012):471–478.
URL http://dx.doi.org/10.1016/j.dam.2011.10.031

A *hole* is a chordless cycle of length at least 5. An *odd hole* is a hole with odd length. An *odd anti-hole* is the complement of an odd hole. A *diamond* is a 4-clique minus an edge. A *paraglider* is a graph having five vertices such that four of them induce a diamond, and the fifth is adjacent to exactly the vertices of degree 2 in the diamond. A *bull* is a graph having five vertices such that four of them induce a chordless path (a P_4) and the fifth is adjacent to exactly the vertices of degree 2 in the P_4. The famous Strong Perfect Graph Theorem by Chudnovsky et al. says that a graph is perfect if and only if it is odd-hole-free and odd-antihole-free. Graph decomposition is one of the fundamental tools for studying graph structure. Two of the most famous decomposition types are *modular decomposition* and *clique separator decomposition*.

Motivated by the study of graph classes related to perfect graphs and the fact that the complexity of the Maximum (Weight) Independent Set (MWIS) problem is an open question for hole-free graphs, we present the following results in the talk:

1. In a paper with Giakoumakis and Maffray, we characterize (hole, paraglider)-free graphs by the structure of their subgraphs having no clique separator. As a consequence, the MWIS problem is solvable in polynomial time on (hole, paraglider)-free graphs.
2. In a paper with Berry, Giakoumakis and Maffray, we describe the structure of (hole, diamond)-free graphs (which is a subclass of (hole, paraglider)-freegraphs) by the structure of their subgraphs having no clique separator and give an $\mathcal{O}(n^2)$ time recognition algorithm for this class.
3. In a paper with Raffaele Mosca, we give a polynomial time algorithm for the MWIS problem on (odd-hole, bull)-free graphs ((odd-hole, dart)-free graphs, respectively).

3.4 Linear recognition of almost (unit) interval graphs

Yixin Cao (Hungarian Academy of Sciences – Budapest, HU)

Main reference Y. Cao, "Linear Recognition of Almost (Unit) Interval Graphs," arXiv:1403.1515v1 [cs.DM], 2014.
URL http://arxiv.org/abs/1403.1515v1

Give a graph class $\mathcal{G}$ and a nonnegative integer k, we use $\mathcal{G}+kv$, $\mathcal{G}+ke$, and $\mathcal{G}-ke$ to denote the classes of graphs that can be obtained from some graph in $\mathcal{G}$ by adding k vertices, adding k edges, and deleting k edges, respectively. They are called *almost (unit) interval graphs* if $\mathcal{G}$ is the class of (unit) interval graphs. Almost (unit) interval graphs are well motivated from computational biology, where the data ought to be represented by a (unit) interval graph while we can only expect an almost (unit) interval graph for the best. For any fixed k, we give linear-time algorithms for recognizing all these classes, and in the case of membership, our algorithms provide also a specific (unit) interval graph as evidence.

When k is part of the input, all the recognition problems are NP-complete. Our results imply that all of them are fixed-parameter tractable parameterized by k, thereby resolving the long-standing open problem on the parameterized complexity of recognizing (unit-)interval $+ ke$, first asked by Bodlaender et al. [1]. Moreover, our algorithms for recognizing (unit-)interval $+ kv$ and (unit-)interval $- ke$ have single-exponential dependence on k and linear dependence on the graph size, which significantly improve all previous algorithms for recognizing the same classes. In particular, we show that: (n and m stand for the numbers of vertices and edges respectively in the input graph)

- interval $- ke$ can be recognized in time $O(6^k \cdot (n + m))$, improved from $O(k^{2k} \cdot n^3 m)$ [Heggernes et al., STOC 2007];
- unit-interval $- ke$ can be recognized in time $O(4^k \cdot (n+m))$, improved from $O(16^k \cdot (m+n))$ [Kaplan et al., FOCS 1994];
- interval $+ kv$ can be recognized in time $O(8^k \cdot (n + m))$, improved from $O(10^k \cdot n^9)$ [Cao and Marx, SODA 2014]; and
- unit-interval $+ kv$ can be recognized in time $O(6^k \cdot (n + m))$, improved from $O(6^k \cdot n^6)$ [Villanger, IPEC 2010].

These problems have natural optimization versions, which are known as graph modification problems. For those related to interval graphs, we show that under certain condition, there always exist optimum solutions that preserve all modules of the input graph. Another important ingredient of our algorithms is combinatorial and algorithmic characterizations of graphs free of small non-interval graphs. These studies might be of their own interest.

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3.5 Convexity in graphs

Tinaz Ekim (Bogaziçi University – Istanbul, TR)

Joint work of Ekim, Tinaz; Erey, Aysel

Let $G = (V, E)$ be a connected graph and $D \subseteq V(G)$. The geodetic closure of D, denoted by $I[D]$, consists of all vertices which lie on some shortest path between two vertices of D. We say that D is a geodetic set if $I[D] = V(G)$. The geodetic number, denoted by $g(G)$, is the cardinality of a minimum geodetic set in G, and a g-set is a geodetic set of minimum cardinality.

As it is NP-hard to compute the g-set already in chordal graphs, the complexity of the problem of finding a g-set is considered in special graph classes. Polynomial time algorithms are designed for split graphs and proper interval graphs among subclasses of chordal graphs, and for distance hereditary graphs, cographs and P_4-sparse graphs. We will briefly exhibit the block decomposition approach which yields a polynomial time algorithm to compute a g-set in monopolar chordal graphs and a superclass of block-cacti. Then we will discuss some other approaches to handle minimum geodetic set problem. In particular, we will consider the following questions: What are the graphs for which some greedy algorithm finds a g-set? What are the graphs for which the simplicial vertices form a g-set? Which graph modification would yield a graph having this property after k operations?

3.6 Tree deletion set has a polynomial kernel

Archontia C. Giannopoulou (Durham University, GB)

Joint work of Giannopoulou, Archontia C. ; Lokshtanov, Daniel; Saurabh, Saket; Suchy, Ondrej
Main reference A. C. Giannopoulou, D. Lokshtanov, S. Saurabh, O. Suchy, "Tree Deletion Set has a Polynomial Kernel (but no $\mathrm{OPT}^{\mathcal{O}(1)}$ approximation)," arXiv:1309.7891v1 [cs.DS], 2013.
URL http://arxiv.org/abs/1309.7891v1

In the Tree Deletion Set problem the input is a graph G together with an integer k. The objective is to determine whether there exists a set S of at most k vertices such that $G \setminus S$ is a tree. The problem is NP-complete and even NP-hard to approximate within any factor of OPT^c for any constant c. In this talk we give a $O(k^4)$ size kernel for the weighted Tree Deletion Set problem.

3.7 Editing to a connected graph of given degrees

Petr A. Golovach (University of Bergen, NO)

Main reference P. A. Golovach, "Editing to a Connected Graph of Given Degrees," arXiv:1308.1802v1 [cs.DS], 2013.
URL http://arxiv.org/abs/1308.1802v1

The aim of edge editing or modification problems is to change a given graph by adding and deleting of a small number of edges in order to satisfy a certain property. We consider the Edge Editing to a Connected Graph of Given Degrees problem that asks for a graph G, non-negative integers d, k and a function $\delta\colon V(G) \to \{1, \ldots, d\}$, whether it is possible to obtain a connected graph G' from G such that the degree of v is $\delta(v)$ for any vertex v by at most k edge editing operations. As the problem is NP-complete even if $\delta(v) = 2$, we are interested in the parameterized complexity and show that Edge Editing to a Connected Graph of Given Degrees admits a polynomial kernel when parameterized by $d + k$. For the special case $\delta(v) = d$, i.e., when the aim is to obtain a connected d-regular graph, the problem is shown to be fixed parameter tractable when parameterized by k only.

3.8 Characterizations of cographs as intersection graphs of paths on a grid

Martin Charles Golumbic (University of Haifa, IL)

Joint work of Cohen, Elad; Golumbic, Martin Charles; Ries, Bernard

A cograph is a graph which does not contain any induced path on four vertices. We characterize those cographs that are intersection graphs of paths on a grid in the following two cases: (i) the paths on the grid all have at most one bend and the intersections concern edges (the B_1-EPG graphs); (ii) the paths on the grid are not bended and the intersections concern vertices (the B_0-VPG graphs).

In both cases, we give a characterization by a family of forbidden induced subgraphs. We further present polynomial-time algorithms to recognize B_1-EPG cographs and B_0-VPG cographs using their cotree.

This work began during the previous Dagstuhl workshop in 2011.

3.9 A near-optimal planarization algorithm

Bart M. P. Jansen (University of Bergen, NO)

Joint work of Jansen, Bart Maarten Paul; Lokshtanov, Daniel; Saurabh, Saket
Main reference B. M. P. Jansen, D. Lokshtanov, S. Saurabh, "A near-optimal planarization algorithm," in Proc. of the 25th Annual ACM-SIAM Symp. on Discrete Algorithms (SODA'14), pp. 1802–1811, SIAM, 2014.
URL http://dx.doi.org/10.1137/1.9781611973402.130

The problem of testing whether a graph is planar has been studied for over half a century, and is known to be solvable in $O(n)$ time using a myriad of different approaches and techniques. Robertson and Seymour established the existence of a cubic algorithm for the more general problem of deciding whether an n-vertex graph can be made planar by at most k vertex deletions, for every fixed k. Of the known algorithms for k-Vertex Planarization, the algorithm of Marx and Schlotter (WG 2007, Algorithmica 2012) running in time $2^{k^{O(k^3)}}n^2$ achieves the best running time dependence on k. The algorithm of Kawarabayashi (FOCS 2009), running in time $f(k)n$ for some $f(k) \geq 2^{k^3}$ that is not stated explicitly, achieves the best dependence on n.

We present an algorithm for k-Vertex Planarization with running time $2^{O(k \log k)}n$, significantly improving the running time dependence on k without compromising the linear dependence on n. Our main technical contribution is a novel scheme to reduce the treewidth of the input graph to $O(k)$ in time $2^{O(k \log k)}n$. It combines new insights into the structure of graphs that become planar after contracting a matching, with a Baker-type subroutine that reduces the number of disjoint paths through planar parts of the graph that are not affected by the sought solution. To solve the reduced instances we formulate a dynamic programming algorithm for Weighted Vertex Planarization on graphs of treewidth w with running time $2^{O(w \log w)}n$, thereby improving over previous double-exponential algorithms.

While Kawarabayashi's planarization algorithm relies heavily on deep results from the graph minors project, our techniques are elementary and practically self-contained. We expect them to be applicable to related edge-deletion and contraction variants of planarization problems.

3.10 Around the listing of minimal dominating sets

Mamadou Moustapha Kante (University Blaise Pascal – Aubiere, FR)

Joint work of Kante, Mamadou Moustapha; Limouzy, Vincent; Mary, Arnaud; Nourine, Lhouari; Uno, Takeaki

The Transversal Problem which consists in the enumeration of minimal hitting sets of a hypergraph in output-polynomial time, ie in time polynomial in the cumulated sizes of the input hypergraph and output set of minimal hitting sets is a long standing open problem (more than a 50 years old problem). Until now a few examples of tractable cases are known,

the most general examples being the k-degenerate hypergraphs and the k-conformal ones. The best known algorithm is the quasi-polynomial algorithm by Fredman and Khachiyan [1]. A dominating set in a graph is a subset of vertices that hits every closed neighborhood. Hence, the enumeration of minimal dominating sets in a graph (DOM Problem) is a special case of the Transversal Problem. We first sketch the proof that the two problems are equivalent in the sense that there is a polynomial delay algorithm for the Transversal Problem iff there is one for the DOM Problem. In a second part we give examples of graphs where the DOM Problem is tractable by emphasing on used techniques:

1. Tractable Cases from Hypergraphs: k-degenerate graphs, undirected path-graphs, ...
2. The case of Bounded clique-width graphs: meta-theorem by Courcelle based on automata and logic. This case is interesting in its own since it transforms the DOM Problem into an enumeration of trees (simulating successful runs) in DAGS.
3. Transformations of instances into enumeration of paths in DAGS: Interval and permutation graphs. This allows to count in polynomial time, and can be extended to several other graph classes: circular-arc graphs, d-trapezoid, ...
4. Mix of hypergraph techniques and graph theoretic: a polynomial delay algorithm for the enumeration of minimal edge dominating sets.

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3.11 On the variants of tree-width

O-joung Kwon (KAIST – Daejeon, KR)

Joint work of Kwon, O-joung; Ok, Seongmin

In this talk, we consider the notion of spaghetti treewidth, directed spaghetti treewidth, and strongly chordal treewidth, which are variants of tree-width. For each of these graph parameters, we show that the class of graphs with this parameter at most two is closed under taking of minors, and give the obstruction set for this class. We also characterize the class, in terms of a tree of cycles with additional conditions. We also show that for an integer k larger than 2, the classes of graphs with spaghetti treewidth, directed spaghetti treewidth, or strongly chordal treewidth, respectively at most k, are not closed under taking minors.

3.12 Introduction to genome assembly and its relation to problems on graphs

Paul Medvedev (Pennsylvania State University, US)

In this talk, we give a short tutorial on genome assembly, focusing on the algorithmic aspects. We first describe the biological problem and then formulate the shortest superstring model and show its limitations. We then describe the de Bruijn graph model, showing its limitations as well as strengths.

In the second part of the talk, we describe a recent algorithm to collapse all the chains in a de Bruijn graph using a small amount of memory. The algorithm works by partitioning the node in the graph using a hash function so that only the nodes with the same hash value need to be loaded into memory at the same time. The hash function is based on the idea of frequency-based minimizers, which allow the nodes to be evenly distributed and the hash function to exhibit structural locality. This second part is joint work with Rayan Chikhi and Antoine Limasset that will appear at RECOMB 2014.

3.13 On the recognition of four-directional orthogonal ray graphs

George B. Mertzios (Durham University, GB)

Orthogonal ray graphs are the intersection graphs of horizontal and vertical rays (i.e. half-lines) in the plane. If the rays can have any possible orientation (left/right/up/down) then the graph is a 4-directional orthogonal ray graph (4-DORG). Otherwise, if all rays are only pointing into the positive x and y directions, the intersection graph is a 2-DORG. Similarly, for 3-DORGs, the horizontal rays can have any direction but the vertical ones can only have the positive direction. The recognition problem of 2-DORGs, which are a nice subclass of bipartite comparability graphs, is known to be polynomial, while the recognition problems for 3-DORGs and 4-DORGs are open. Recently it has been shown that the recognition of unit grid intersection graphs, a superclass of 4-DORGs, is NP-complete. In this paper we prove that the recognition problem of 4-DORGs is polynomial, given a partition $\{L, R, U, D\}$ of the vertices of G (which corresponds to the four possible ray directions). For the proof, given the graph G, we first construct two cliques G_1, G_2 with both directed and undirected edges. Then we successively augment these two graphs, constructing eventually a graph $\widetilde{G}$ with both directed and undirected edges, such that G has a 4-DORG representation if and only if $\widetilde{G}$ has a transitive orientation respecting its directed edges. As a crucial tool for our analysis we introduce the notion of an S-orientation of a graph, which extends the notion of a transitive orientation. We expect that our proof ideas will be useful also in other situations. Using an independent approach we show that, given a permutation π of the vertices of U (π is the order of y-coordinates of ray endpoints for U), while the partition $\{L, R\}$ of $V \setminus U$ is not given, we can still efficiently check whether G has a 3-DORG representation.

3.14 Vector connectivity in graphs

Martin Milanic (University of Primorska, SI)

Joint work of Boros, Endre; Cicalese, Ferdinando; Heggernes, Pinar; van 't Hof, Pim; Milanič, Martin; Rizzi, Romeo;
Main reference P. Heggernes, P. van 't Hof, Pim, M. Milanič, "Vector connectivity in graphs," Networks, online version, February 2014.
URL http://dx.doi.org/10.1002/net.21545

Motivated by challenges related to domination, connectivity, and information propagation in social and other networks, we introduce and study the Vector Connectivity problem. This

problem takes as input a graph G and an integer $r(v)$ for every vertex v of G, and the objective is to find a vertex subset S of minimum cardinality such that every vertex v either belongs to S, or is connected to at least $r(v)$ vertices of S by disjoint paths. If we require each path to be of length exactly 1, we get the well-known vector domination problem, which is a generalization of the dominating set and vertex cover problems. Consequently, the vector connectivity problem becomes NP-hard if an upper bound on the length of the disjoint paths is also supplied as input. Due to the hardness of these domination variants even on restricted graph classes, like split graphs, Vector Connectivity seems to be a natural problem to study for drawing the boundaries of tractability for this type of problems. We show that Vector Connectivity can actually be solved in polynomial time on split graphs, in addition to cographs and trees.

We also show that the problem is NP-hard for planar line graphs and for planar bipartite graphs, APX-hard on general graphs, and can be approximated in polynomial time within a factor of $\log n + 2$ on all n-vertex graphs.

Vertex covers and dominating sets in a graph G can be easily characterized as hitting sets of derived hypergraphs (of G itself, and of the closed neighborhood hypergraph of G, respectively). Using Menger's Theorem, we give a similar characterization of vector connectivity sets.

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3.15 Parameterized algorithms for Max Colorable Induced Subgraph problem on perfect graphs

Neeldhara Misra (Indian Institute of Science, IN)

Joint work of Misra, Neeldhara; Panolan, Fahad; Rai, Ashutosh; Raman, Venkatesh; Saurabh, Saket
Main reference N. Misra, F. Panolan, A. Rai, Ve. Raman, S. Saurabh, "Parameterized Algorithms for Max Colorable Induced Subgraph Problem on Perfect Graphs," in Proc. of the 39th Int'l Workshop on Graph-Theoretic Concepts in Computer Science (WG'13), LNCS, Vol. 8165, pp. 370–381, Springer, 2013.
URL http://dx.doi.org/10.1007/978-3-642-45043-3_32

We explore the parameterized complexity of Max Colorable Induced Subgraph on perfect graphs. The problem asks for a maximum sized q-colorable induced subgraph of an input graph G. Yannakakis and Gavril (IPL 1987) showed that this problem is NP-complete even on split graphs (which is a proper subset of perfect graphs, chordal graphs and co-chordal graphs). However, they showed that for fixed q, the problem is solvable in time $n^{O(q)}$ on chordal graphs. A natural question is whether the problem is fixed parameter tractable (FPT) when parameterized by the number of colors q, that is, whether the problem admits an algorithm with running time $f(q)n^{O(1)}$. A simple reduction shows that the problem is W[2]-hard parameterized by q, even on split graphs. Thus, we study this problem with another natural parameter – the solution size – l.

We design two parameterized algorithms for the problem. The first one runs in time $5.44^l(n + \#\alpha(G))^{O(1)}$ where $\#\alpha(G)$ is the number of maximal independent sets of the

input graph and the second algorithm runs in time $q^{(l+o(l))}n^{O(1)}$. Observe that since $q < l$ for all non-trivial situations, we have that the second algorithm is FPT in l alone. The first algorithm is efficient when the input graph contains only polynomially many maximal independent sets; for example split graphs and co-chordal graphs. Finally, we show that (under standard complexity-theoretic assumptions) the problem does not admit a polynomial kernel even on split graphs and on perfect graphs the problem does not admit a polynomial kernel even for fixed values of $q > 1$.

3.16 Certifying FPT-algorithms

Haiko Müller (University of Leeds, GB)

Joint work of Mueller, Haiko; Wilson, Samuel
Main reference H. Müller, S. Wilson, "An FPT Certifying Algorithm for the Vertex-Deletion Problem," in Proc. of the 24th Int'l Workshop on Combinatorial Algorithms (IWOCA'13), LNCS, Vol. 8288, pp. 468–472, Springer, 2013.
URL http://dx.doi.org/10.1007/978-3-642-45278-9_45

We propose a scheme of certifying FPT-algorithms for vertex-deletion problems on graphs. For a class C of graphs that is closed under a partial order $<$ these algorithms decide, for a fixed integer k, whether a given graph G has a set U of at most k vertices such that $G - U$ belongs to C. That is, these algorithms recognize the class $C + kv$ of graphs in time $f(k)n^c$ for some constant c. In the affirmative case the algorithm should also provide the user with such a set U of vertices, and otherwise it should point out an obstruction of $C + kv$ in G. For instance, if $<$ is the ordering defined by induced subgraphs then the obstruction will be a minimal forbidden subgraph.

We give conditions on the partial order $<$ that are necessary or sufficient for such certifying FPT-algorithms to exist for all classes C that are closed under $<$ and have a finite obstruction set with respect to $<$. Moreover we illustrate these conditions by examples, namely the partial orders defined by vertex deletion, edge deletion, vertex dissolution and edge contraction, or combinations thereof.

3.17 On the complexity of degree anonymization

Andre Nichterlein (TU Berlin, DE)

Joint work of Bazgan, Cristina; Froese, Vincent; Hartung, Sepp; Nichterlein, Andre; Niedermeier, Rolf; Suchy, Ondrej
Main reference S. Hartung, A. Nichterlein, R. Niedermeier, and O. Suchy, "A refined complexity analysis of degree anonymization on graphs," in Proc. of the 40th Int'l Colloquium on Automata, Languages, and Programming (ICALP'13), LNCS, Vol. 7966, pp. 594–606, Springer, 2013.
URL http://dx.doi.org/10.1007/978-3-642-39212-2_52

Motivated by a growing interest in graph anonymization (in particular with respect to social networks), we study the NP-hard Degree Anonymity problem asking whether a graph can be made k-anonymous by adding at most a given number of edges. Herein, a graph is k-anonymous if for every vertex in the graph there are at least $k-1$ other vertices of the same degree. We show that the problem is intractable when considering the standard parameter solution size, even when searching for parameterized approximation algorithms. Contrasting these negative results, we prove fixed-parameter tractability for the parameter maximum vertex degree and experimentally evaluate the corresponding algorithm.

3.18 Subexponential parameterized complexity of completion problems

Marcin Pilipczuk and Michał Pilipczuk (University of Bergen, NO)

Let Π be a fixed hereditary graph class. In the Π Completion problem, given a graph G and an integer k, we ask whether it is possible to add at most k edges to G to obtain a member of Π. In the recent years completion problems received significant attention from the perspective of parameterized complexity, with the standard parameterization by k.

In our tutorial we first survey the history of the study of parameterized complexity of completion problems, including the breakthrough paper of Villanger et al [6] that settles fixed-parameter tractability of Interval Completion, as well as recent advancements on polynomial kernelization. Then, we move to the main topic of the tutorial, namely subexponential parameterized algorithms.

First fixed-parameter algorithms for completion problems focused mostly on the 'forbidden induced subgraphs' definition of the graph class Π in question. In 2012 Fomin and Villanger [4] came up with a novel idea to instead focus on some structural definition of the class Π, trying to build the modified output graph by dynamic programming. Slightly simplifying, we may say that the main technical contribution of [4] is a bound of at most $k^{\mathcal{O}(\sqrt{k})}$ reasonable 'partial chordal graphs' for an input instance (G, k) of Chordal Completion. Consequently, Chordal Completion can be solved in $k^{\mathcal{O}(\sqrt{k})} + n^{\mathcal{O}(1)}$ time. Following the approach of Fomin and Villanger, in the past two years subexponential parameterized algorithms were shown for the class of chain [4], split [5], threshold [3], trivially perfect [3], pseudosplit [3] and, very recently, proper interval [2] and interval [1] graphs. Moreover, a few lower bounds for related graph classes were found [3].

In our tutorial we present the approach of Fomin and Villanger on the example of Trivially Perfect Completion, and then survey the main ideas needed in the remaining algorithms.

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3.19 Optimal Erdős Pósa for pumpkins revisited

Dimitrios M. Thilikos (ALGCo project team, CNRS, LIRMM, Montpellier, FR, and Department of Mathematics, National and Kapodistrian University of Athens, GR)

Joint work of Chatzidimitriou, Dimitris; Sau, Ignasi; Raymond, Jean-Florent; Thilikos, Dimitrios M.

Given two graphs H and G, we denote by $\mathbf{pack}^{\mathbf{v}}_H(G)$ the maximum number of vertex-disjoint minor models of H in G. We denote by $\mathbf{pack}^{\mathbf{e}}_H(G)$ the maximum number of edge-disjoint minor models of H in G. We also denote by $\mathbf{cover}^{\mathbf{v}}_H(G)$ the minimum number of vertices that intersect all minor models of H in G. Similarly, by $\mathbf{cover}^{\mathbf{e}}_H(G)$ we denote the minimum number of edges that intersect all minor models of H in G. Finally, we denote by θ_r the multi-graph containing two vertices and r parallel edges between them (also known as *the r-pumpkin*).

We prove the following results.

▶ **Theorem 1.** *There exists a function $f : \mathbb{N} \to \mathbb{N}$ such that for every two positive integers r, q, and every graph G excluding K_q as a minor, it holds that $\mathbf{cover}^{\mathbf{v}}_{\theta_r}(G) \leq f(r) \cdot \mathbf{pack}^{\mathbf{v}}_{\theta_r}(G) \cdot \log q$.*

▶ **Theorem 2.** *There exists a function $f : \mathbb{N} \to \mathbb{N}$ such that for every two positive integers r, q, and every graph G excluding K_q as a minor, it holds that $\mathbf{cover}^{\mathbf{e}}_{\theta_r}(G) \leq f(r) \cdot \mathbf{pack}^{\mathbf{e}}_{\theta_r}(G) \cdot \log q$.*

The above results also imply that, for every r, the problems of computing the values of $\mathbf{pack}^{\mathbf{v}}_{\theta_r}$, $\mathbf{cover}^{\mathbf{v}}_{\theta_r}$, $\mathbf{pack}^{\mathbf{e}}_{\theta_r}$, and $\mathbf{cover}^{\mathbf{e}}_{\theta_r}$ admit $\log(OPT)$-approximation (deterministic and polynomial) algorithms.

3.20 Parameterized complexity dichotomy for Steiner multicut

Erik Jan van Leeuwen (MPI für Informatik – Saarbrücken, DE)

Joint work of Bringmann, Karl; Hermelin, Danny; Mnich, Matthias; van Leeuwen, Erik Jan

We consider the Steiner Multicut problem, which asks, given an undirected graph G, a collection $T_1, \ldots, T_t \subseteq V(G)$, of terminal sets of size at most p, and an integer k, whether there is a set S of at most k edges or nodes such that of each set T_i at least one pair of terminals is in different connected components of $G \setminus S$. This problem generalizes several well-studied graph cut problems, in particular the Multicut problem, which corresponds to the case $p = 2$. We provide a dichotomy of the parameterized complexity of Steiner Multicut on general graphs. That is, for any combination of k, t, p, and the treewidth $tw(G)$ as a constant, parameter, or unbounded, and for all versions of the problem (edge deletion, and node deletion with and without deletable terminals), we prove either that the problem is fixed-parameter tractable or that the problem is hard (W[1]-hard or even (para-) NP-complete). Among the many results in the paper, we highlight that:

- The edge deletion version of Steiner Multicut is fixed-parameter tractable for the parameter $k + t$ on general graphs (but has no polynomial kernel, even on trees).
- In contrast, both node deletion versions of Steiner Multicut are W[1]-hard for the parameter $k + t$ on general graphs.

- All versions of Steiner Multicut are W[1]-hard for the parameter k, even when $p = 3$ and the graph is a tree plus one node. This means that the known parameterized algorithms of Marx and Razgon, and Bousquet et al. (STOC 2011) for Multicut do not generalize to even the most basic instances of Steiner Multicut.

Since we allow k, t, p, and $tw(G)$ to be any constant, our characterization includes a dichotomy for Steiner Multicut on trees (i.e., for $tw(G) = 1$) as well as a polynomial-time versus NP-hardness dichotomy (by restricting $k, t, p, tw(G)$ to a constant or unbounded).

3.21 Parametrized algorithm for weighted independent set problem in bull-free graphs

Kristina Vušković (University of Leeds, GB)

Joint work of Thomassé, Stéphan; Trotignon, Nicolas; Vušković, Kristina
Main reference S. Thomassé, N. Trotignon, K. Vušković, "Parameterized algorithm for weighted independent set problem in bull-free graphs," arXiv:1310.6205v1 [cs.DM], 2013.
URL http://arxiv.org/abs/1310.6205v1

The bull is the graph obtained from a triangle by adding two pendant nonadjacent edges. A graph is bull-free if it does not contain a bull as an induced subgraph. We show the existence of an FPT algorithm for weighted independent set problem for bull-free graphs (parametrized by solution size). While a polynomial kernel is unlikely to exist for this problem, we show however that the problem has a polynomial size Turing-kernel. As a byproduct, if we forbid odd holes in addition to the bull, we show the existence of a polynomial time algorithm for the independent set problem. We also prove that the chromatic number of a bull-free graph is bounded by a function of its clique number and the maximum chromatic number of its triangle-free induced subgraphs. All our results rely on a decomposition theorem of bull-free graphs due to Chudnovsky which is modified here, allowing us to provide extreme decompositions, adapted to our computational

4 Open Problems

4.1 Treecost as a parameterized problem

Hans L. Bodlaender (Utrecht University, NL)

Let f be a function on the natural numbers. Consider the following problem. Given a graph G, and an integer L, is there a chordal supergraph H of G such that the sum over all maximal cliques C in H of $f(|C|)$ is at most L.

What is the complexity of the problem when parameterized by L?

4.2 Two simple edge editing problems

Henning Fernau (Universität Trier, DE)

We propose two graph modification problems mentioned by Damaschke and Mogren in [1].

- Edit Into Clique & Isolates
  Given a graph G of order n and an integer k, is it possible to turn G into one clique K_ℓ and a collection of $n-\ell$ isolates by adding or removing at most k edges from G?
  This problem is termed $K_1[0]$ Bag Editing in [1].
- Edit Into Biclique & Isolates
  Given a graph G of order n and an integer k, is it possible to turn G into one biclique $K_{j,\ell}$ and a collection of $n-j-\ell$ isolates by adding or removing at most k edges from G?
  This corresponds to P_3 Bag Editing from [1] by graph complementation.

In both cases, it was open whether the problem is NP-hard or whether it can be solved in polynomial time.

Edit Into Clique & Isolates was shown NP-hard in the course of the seminar by André Nichterlein.

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4.3 More graph editing problems

Henning Fernau (Universität Trier, DE)

The typical graph editing problems seen during this seminar are to delete at most i vertices, or to delete at most j edges, or to insert at most k edges from a given graph G of order n and size m to obtain a target graph that satisfies certain properties P. Often, such properties can be specified by (induced) subgraphs or similar substructures. There are several related problems that might be worth studying, as well. From the perspective of parameterized complexity, the "dual problems" could be interesting to study. This could mean:

- Delete vertices from G such that the target graph satisfying P contains at least $i_d = n - i$ vertices. In other words, does there exist an induced subgraph of G on at least i_d vertices that satisfies P?
- Delete edges from G such that the target graph satisfying P contains at least $j_d = m - j$ edges. In other words, does there exist a subgraph of G on at least j_d vertices that satisfies P?
- Add edges to G such that the target graph satisfying P contains at least $k_d = (n^2 - n)/2 - m + k$ edges. The upper bound $(n^2 - n)/2 - m$ is derived from the fact that adding edges corresponds to deleting edges in the complement graph.

Also, there are natural lower bounds for these problems in terms of packings, assuming that P is given by a set of forbidden structures (e.g., forbidden induced subgraphs) S_P. We would arrive at problems like:

- Can we find a vertex-disjoint packing of G with i_p objects from S_P?
- Can we find an edge-disjoint packing of G with j_p objects from S_P?

Possibly, stranger problems would show up when defining packing problems for edge-addition problems. This seems to necessitate a forbidden substructure characterization of the complement graphs. There could be also other related packing problems, for instance:

- Can we add some vertices and edges to the graph G so that the resulting graph H admits a "perfect packing" with at most ℓ objects from S_P?

Here, "perfect packing" could either mean that all vertices or that all edges of H are covered by the at most ℓ objects from S_P. An example for such a problem can be found in [1]. This might also answer a question raised by one of the participants of the seminar about the meaningful existence of vertex addition problems.

To our knowledge, far less recent work on the graph (modification) problems sketched above has been done. In particular, general question on when such problems are hard or easy in the parameterized sense could be posed. Also, the existence of sub-exponential algorithms for such types of problems should be interesting to look into.

Clearly, $i_p \leq i$ and $j_p \leq j$, so that also the question of "parameterizing above guaranteed value" shows up, which has not been in the focus of talks from the seminar, either.

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4.4 Modification into graph classes

George B. Mertzios (Durham University, GB)

Let $\mathcal{C}_1$ and $\mathcal{C}_2$ be two graph classes. Then, given a graph $G = (V, E) \in \mathcal{C}_1$, what is the complexity of each of the problems:

- compute a minimum set F of edges such that the graph $G' = (V, E \cup F)$ belongs to class $\mathcal{C}_2$ (*completion* problem);
- compute a minimum set $F \subseteq E$ of edges such that the graph $G' = (V, E \setminus F)$ belongs to class $\mathcal{C}_2$ (*edge deletion* problem);
- compute a minimum set $U \subseteq V$ of vertices such that the graph $G' = G[U]$ belongs to class $\mathcal{C}_2$ (*vertex deletion* problem).

For which classes $\mathcal{C}_1, \mathcal{C}_2$ are the above problems solvable in polynomial or FPT time? For instance, what is the complexity of these problems in the case where $\mathcal{C}_1$ is the class of interval graphs and $\mathcal{C}_2$ is the class of proper interval graphs?

4.5 H-minor sequences

Daniel Paulusma (Durham University, GB)

Joint work of Golovach, Petr; Paulusma, Daniel; Stewart, Iain
Main reference P. A. Golovach, D. Paulusma, I. A. Stewart, "Graph editing to a fixed target," in Proc. of the 24th Int'l Workshop on Combinatorial Algorithms (IWOCA'13), LNCS, Vol. 8288, pp. 192–205, Springer, 2013.
URL http://dx.doi.org/10.1007/978-3-642-45278-9_17

Call a sequence of operations, each of type "edge contraction", "edge deletion" or "vertex deletion", that modifies a graph G into a graph H an *H-minor sequence*. The *length* of an H-minor sequence is the number of its operations.

For a fixed graph H, let H-Minor Sequence be the problem that asks whether a given graph G has an H-minor sequence of length at most ℓ for some given integer ℓ. There are many graphs H for which this problem is known to be polynomial-time solvable, and many graphs H for which this problem is known to be NP-complete.

Let C_k be the cycle on k vertices. It is known that C_k-Minor Sequence is polynomial-time solvable for every $k \leq 4$. We pose the following problem:

Determine the computational complexity of C_k-Minor Sequence for any fixed $k \geq 5$.

4.6 Open problems from the tutorial on subexponential parameterized complexity of completion problems

Marcin Pilipczuk (University of Bergen, NO)

Let Π be a fixed hereditary graph class. In the Π Completion problem, given a graph G and an integer k, we ask whether it is possible to add at most k edges to G to obtain a member of Π. During the tutorial on subexponential parameterized complexity of completion problems and the discussion on open problem session following the tutorial the following interesting open problems were identified.

1. For most of known subexponential parameterized algorithm for completion problems the dependency on the parameter in the running time is $k^{\mathcal{O}(\sqrt{k})}$ or better, with the exception of Proper Interval Completion where the dependency is $k^{\mathcal{O}(k^{2/3})}$ [2]. Can it be improved to $k^{\mathcal{O}(\sqrt{k})}$?
2. The running time of the algorithm for Split Completion [4] has dependency $2^{\mathcal{O}(\sqrt{k})}$ on the parameter. Can we obtain such a dependency for other problems?
3. We believe that for the discussed graph classes Π, no FPT algorithm with dependency $2^{o(\sqrt{k})}$ on the parameter should exist, as it would be also a $2^{o(n)}$-time algorithm. Can we prove this conjecture for some discussed graph classes Π, under the assumption of the Exponential Time Hypothesis? We remark that to achieve this goal most likely one would need to reengineer the known NP-hardness reductions for these completion problems, as the only currently known reductions use Optimal Linear Arrangement as a pivot problem, causing at least cubic blowup in the parameter.
4. In scope of the techniques used in the recent subexponential parameterized algorithm for Interval Completion [1], a question of a polynomial kernel for this problem is appealing.

5. We conjecture that for an instance (G, k) of Chordal Completion, one can enumerate a family $\mathcal{F}$ of $n^{\mathcal{O}(\sqrt{k})}$ subsets of $V(G)$ such that for any chordal supergraph H of G with $|E(H) \setminus E(G)| \leq k$, all maximal cliques of H belong to $\mathcal{F}$. This statement does not follow from the work of Fomin and Villanger [3], as in some cases the algorithm of [3] identifies and executes a subexponential branching.
6. For the search of further subexponential parameterized algorithms for completion problems, the following interesting graph classes have been identified: weakly chordal graphs, strongly chordal graphs, permutation graphs, perfect graphs, 3-leaf powers and path graphs. Of particular importance is the case of Perfect Completion, where no fixed-parameter algorithm is known.

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4.7 Open problem: Eulerian SCC Deletion

Marcin Pilipczuk (University of Bergen, NO)

In the Eulerian SCC Deletion problem, given a directed graph G and an integer k, we ask whether it is possible to delete at most k arcs from G to obtain a graph where each strongly connected component contains an Euler tour. Is Eulerian SCC Deletion fixed-parameter tractable, when parameterized by k?

A few remarks are in place. The question of fixed-parameter tractability of Eulerian SCC Deletion was originally posted by Cechlárová and Schlotter in [1], where it appeared naturally in modelling of housing markets. A somehow related deletion problems were studied in [2]. However, it is not hard to reduce Directed Feedback Vertex Set to Eulerian SCC Deletion, and, hence, we expect that a hypothetical fixed-parameter algorithm for Eulerian SCC Deletion would need to use substantially different techniques than the ones developed in [2].

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4.8 Existence of Polynomial Kernel for Edge-Disjoint Paths

Erik Jan van Leeuwen (MPI für Informatik – Saarbrücken, DE)

The Vertex-Disjoint Paths problem takes as input a graph G and a set of k pairs of terminals in G, and one should decide whether there exist k pairwise vertex-disjoint paths in G such that the vertices in each terminal pair are connected to each other by one of the paths. In the Edge-Disjoint Paths problem, the paths should be edge-disjoint instead of vertex-disjoint. It is known that both problems are NP-hard on general graphs [4, 2], but fixed-parameter tractable when parameterized by k [5]. Recently, in joint work with Pinar Heggernes, Pim van 't Hof, and Reza Saei, I showed that both problems remain NP-hard on the class of split graphs, which are graphs whose vertex set can be partitioned into an independent set and a clique. Moreover, we showed that both problems admit a polynomial kernel on split graphs when parameterized by k [3]. This is the first polynomial kernel for both problems on graph classes. On general graphs, it is known that Vertex-Disjoint Paths does not admit a polynomial kernel when parameterized by k, unless NP $\subseteq$ coNP/poly [1]. However, for Edge-Disjoint Paths, no such result seems to be known. Therefore, we ask whether or not there exists a polynomial kernel for Edge-Disjoint Paths on general graphs when parameterized by k?

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Report from Dagstuhl Seminar 14072

New Perspectives in Shape Analysis

Edited by

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Abstract

Over the last decade, it has become increasingly affordable to digitize 2-D and 3-D shape information using multiple modalities, such as (video) cameras, image-based reconstruction systems, laser-range scanners, or depth cameras. If these dense models can be processed and described in an efficient and informative way, they can be used in applications, such as ergonomic design, virtual shopping, scientific and medical visualization, realistic simulation, photo-realistic rendering, the design of natural user interfaces, and semantic scene understanding.

Traditionally, the notion of shape has been studied either by analyzing projections of shapes in images or by analyzing a sparse set of marker positions on 3-D shapes. Typical tasks in 2-D shape analysis include segmenting objects in images and tracking objects across a sequence of images, and typical tasks in 3-D shape analysis include reconstructing the three-dimensional object depth from input images and identifying corresponding points on different 3-D models. The analysis and processing of shape data becomes especially challenging because of the increasing amount of data captured by sensors used to acquire shapes, and because modern applications such as natural user interfaces require real-time processing of the input shapes.

Meeting these challenges requires models of shape analysis that are compact and informative, thereby allowing the development of algorithms that can process large datasets efficiently. To achieve these goals, interdisciplinary approaches are needed that use concepts from a variety of research areas, including numerical computing, differential geometry, deformable shape modeling, sparse data representation, and machine learning. On the algorithmic side, many shape analysis tasks are modeled using partial differential equations, which can be solved using tools from the field of numerical computing. The fields of differential geometry and deformable shape modeling have recently begun to influence shape analysis methods. Furthermore, tools from the field of sparse representations, which aim to describe input data using a compressible representation with respect to a set of carefully selected basis elements, have the potential to significantly reduce the amount of data that needs to be processed in shape analysis tasks. The related field of machine learning offers similar potential.

This seminar brought together 28 researchers from North America and Europe engaged in recent and upcoming developments in shape analysis who view these challenges from different perspectives and who together discussed the pressing open problems and novel solutions to them.

Seminar February 9–14, 2014 – http://www.dagstuhl.de/14072

1998 ACM Subject Classification G.1.3 Numerical Linear Algebra, G.1.8 Partial Differential Equations, I.2.10 Vision and Scene Understanding, I.3.5 Computational Geometry and Object Modeling, I.3.7 3-D Graphics and Realism, I.4.6 Segmentation, I.4.8 Scene Analysis, I.4.10 Image Representation, I.5.4 Applications

Keywords and phrases shape analysis, mathematical morphology, shape reconstruction, sparsity, machine learning, numerical computing, level set methods, optimisation methods

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Edited in cooperation with Yong Chul Ju

1 Executive Summary

Michael Breuß
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Dagstuhl seminar 14072 *New Perspectives in Shape Analysis* took place February 9–14, 2014. 28 researchers from North America and Europe discussed state-of-the-art, current challenges, and promising future research directions in the areas of 2-D and 3-D shape analysis from a cross-disciplinary point of view. Participants included international experts from the fields of continuous-scale shape analysis, discrete shape analysis and sparsity, and numerical computing. The seminar consisted of an opening session, 11 scientific presentation sessions, as well as a break-out session, which provided room for in-depth discussions in small groups. Furthermore, there was time for extensive discussions both between the talks and in the evenings.

This seminar was motivated by the observation that in everyday life, geometric shapes surround us, and that the understanding of concepts describing these shapes is at the heart of various applications, such as ergonomic design, virtual shopping, scientific and medical visualization, realistic simulation, the design of natural user interfaces, and semantic scene understanding. Traditionally, the notion of shape has been studied either by analysing a sparse set of marker positions on 3-D shapes, mostly for medical imaging applications, or by analysing projections of shapes in 2-D images, mostly for image processing and computer vision applications. New challenges in the analysis and processing of such data arise with the increasing amount of data captured by sensors used to acquire shapes, and with modern applications such as natural user interfaces that require real-time processing of the input shapes. Recently, it has become increasingly affordable to digitise 3-D shapes using multiple modalities, such as laser-range scanners, image-based reconstruction systems, or depth cameras like the Kinect sensor. Using these dense 3-D shapes in the above mentioned applications requires processing and describing the shapes in an efficient and informative way.

The purpose of this seminar was to address these challenges with the latest tools related to geometric, algorithmic and numerical concepts. To do so, we brought together researchers working on shape analysis topics from different perspectives.

As the analysis of 3-D shapes and deformable shape models have received much interest recently, classic shape analysis tools from differential geometry have a fresh influence in the field. Being related to the issue how to represent shapes efficiently, the research areas of sparse data representation and machine learning have begun to influence shape analysis modelling and the numerics. Especially in the context of three-dimensional data (or even higher-dimensional data sets), efficient optimization methods will certainly become increasingly important since many shape analysis models can be cast in the form of an optimization problem.

While the fields of modelling and numerical computing are strongly related when it comes to shape analysis applications, modelling is seen as a hot topic in computer science while numerical computing is often seen as a mathematical domain. The purpose in bringing together researchers from those different communities sharing substantial interest in shape analysis was to explore the benefits of a *cross-disciplinary* point of view. More specifically,

- researchers in continuous-scale shape analysis brought to the meeting their knowledge of differential and variational models and also of classic numerical methods in the field,
- researchers in discrete shape analysis and sparsity brought to the meeting their knowledge about the latest techniques in efficient data representations and related machine learning techniques, as well as efficient data structures and discrete optimization methods, and
- researchers in numerical computing brought to the meeting their knowledge of numerical techniques for PDEs and optimization.

As the demands in the individual fields are high, the research groups in which the most interesting techniques are proposed are quite specialised. This not only holds for discrete and continuous-scale modelling and numerical computing, but also for the areas of sparsity and machine learning that were discussed during this seminar. Because of this, there is no regular conference or workshop that serves as a meeting place for an exchange of ideas of these groups.

Promising new ways to combine the latest techniques from these different fields were identified during in-depth discussions in small groups. Some especially promising research directions in the areas of intrinsic structure detection, co-segmentation of shapes, shape from shading, modelling deformable shapes, and models for face shapes, were discussed in small groups during the break-out session.

2 Table of Contents

3 Overview of Talks

3.1 An operator approach to geometry processing

Mirela Ben-Chen (Technion – Haifa, IL)

Joint work of Ben-Chen, Mirela; Azencot, Omri; Ovsjanikov, Maks; Chazal Fred
Main reference O. Azencot, M. Ben-Chen, F. Chazal, M. Ovsjanikov, "An Operator Approach to Tangent Vector Field Processing," Computer Graphics Forum, 32(5):73–82, 2013.
URL http://dx.doi.org/10.1111/cgf.12174

A fundamental task in the analysis of geometric shapes is the choice of representation of differential quantities. Different representations will lead to different optimization problems, and can considerably influence the scope of feasible applications. We will describe a novel choice of representation, based on functional operators, which although standard in classic differential geometry has only been recently applied to geometry processing. We will show how operators which take scalar functions to scalar functions can be used to concisely represent smooth maps between shapes and smooth vector fields. We further demonstrate that by using a common operator representation, the intimate connection between maps and vector fields can be leveraged to easily compute vector fields which fulfill intricate global constraints, such as Killing and symmetric vector fields. Finally, we discuss additional geometric properties which can be represented as operators.

3.2 Combination of piecewise-geodesic paths for interactive segmentation

Sébastien Bougleux (Caen University, FR)

Joint work of Mille, Julien; Bougleux, Sebastien; Cohen, Laurent D.
Main reference J. Mille, S. Bougleux, L. D. Cohen, "Combination of paths for interactive segmentation," in Proc. of the British Machine Vision Conf. 2013, pp. 133.1–133.11, BMVA Press, 2013.
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When it is desired to segment interactively an object of interest in an image, it is natural to position points manually along the contour of the object. By constructing a path between each pair of consecutive control points and by joining these paths end-to-end, a closed contour is obtained. The resulting contour may not be simple and may not follow the object's contour everywhere. These problems may occur when control points are irregularly distributed or when the contour is poorly represented. To overcome these problems, we propose a method guaranteeing a simple and closed contour while being robust to the initial placement of the control points. The central idea is to consider several possible paths per pair of consecutive control points, and to select the combination of paths so that the resulting contour is closed, and as simple as possible. To this, we focus on a wider category of paths, called *piecewise geodesic*, and we propose an energy functional combining classical *edge* and *region* terms with a new term which favors curves to be simple. This term penalizes recoveries and self-intersections. Given n control points and K paths per couple of consecutive points, we also introduce a heuristic algorithm in $O(Kn^2)$ for determining a satisfactory combination, instead of an exhaustive search in $O(K^n)$. Comparison against the geodesically linked active contour model and the Riverbed algorithm, which have similar inputs and purposes, demonstrated the advantages of our approach.

3.3 Is there a good coordinate system for shape from shading?

Michael Breuß (BTU Cottbus, DE)

Joint work of Galliani, Silvano; Ju, Yong Chul; Breuß, Michael; Bruhn, Andrés
Main reference S. Galliani, Y. C. Ju, M. Breuß, A. Bruhn, "Generalised Perspective Shape from Shading in Spherical Coordinates," in Proc. of the 4th Int'l Conf. on Scale Space and Variational Methods in Computer Vision (SSVM'13), LNCS, Vol. 7893, pp. 222-233, Springer, 2013.
URL http://dx.doi.org/10.1007/978-3-642-38267-3_19

In this talk some recent results are presented making use of spherical coordinates for perspective shape from shading. The aim of the talk is to inspire some discussion about good coordinate systems for shape from shading, and probably for shape-from-X-tasks more generally.

3.4 Joint diagonalization methods for deformable shape analysis

Michael M. Bronstein (University of Lugano, CH)

Joint work of Bronstein, Michael M.; Bronstein, Alexander M.; Kovnatsky, Artiom; Kimmel, Ron; Glashoff, Klaus
Main reference A. Kovnatsky, M. M. Bronstein, A. M. Bronstein, K. Glashoff, R. Kimmel, "Coupled quasi-harmonic bases," Computer Graphics Forum, 32(2pt4):439–448, 2013.
URL http://dx.doi.org/10.1111/cgf.12064

I will present our recent work in which we introduced joint diagonalization methods, previously used for blind separation of signals, into the analysis of deformable shapes. I will show how these methods can be applied to problems of shape correspondence, similarity, and editing, and discuss their relations to other interesting recent works in the field.

3.5 Hierarchical Representation of Cell Complexes for Topological Shape Analysis

Leila De Floriani (University of Genova, IT)

Joint work of De Floriani, Leila; Lidija, Comic; Federico Iuricich; Ulderico Fugacci
Main reference L. Comic, L. De Floriani, F. Iuricich, U. Fugacci, "Topological Modifications and Hierarchical Representation of Cell Complexes in Arbitrary Dimensions," Computer Vision and Image Understanding, Vol. 121, pp. 2–12, 2014.
URL http://dx.doi.org/10.1016/j.cviu.2013.11.011

In this talk, we present a hierarchical approach to homology computation and topological analysis on cell complexes of arbitrary dimensions. Specifically, we briefly review a set of atomic Euler operators for simplifying and refining cell complexes. We have shown that such operators form a minimally complete set for updating cell complexes. Based on them, we have developed a hierarchical model for cell complexes, the we call a Hierarchical Cell Complex (HCC), which allows extracting representations of the original complex at both uniform and variable resolutions. We discuss our implementation of the HCC based on homology-preserving Euler operators, and we show the effectiveness of such a hierarchical model in computing homology generators efficiently and at different resolutions. We discuss on-going work on extending the HCC to the case of simplicial complexes.

3.6 Image segmentation with level set trees

Anastasia Dubrovina (Technion – Haifa, IL)

Joint work of Dubrovina, Anastasia; Hershkovitz, Rom; Kimmel, Ron

Several image editing tasks, such as segmentation, matting and colorization, employ an intrinsic distance measure defined in the image domain, to propagate information from user defined set of constraints, to the whole image. In this talk we will show that this problem can be alternatively defined in the domain of the level sets of an image, and solved by traversing the tree of level sets. We will further show application of proposed method for user-assited image segmentation. Based on joint work with Ron Kimmel and Rom Hershkovitz.

3.7 Are Fast Solvers for Hamilton-Jacobi equations really reliable?

Maurizio Falcone (University of Rome "La Sapienza", IT)

Joint work of Cacace, Simone; Cristiani, Emiliano; Falcone, Maurizio
Main reference S. Cacace, E. Cristiani, M. Falcone, "Can local single-pass methods solve any stationary Hamilton-Jacobi-Bellman equation?" to appear in SIAM J. Sci. Comput.; availabe as pre-print as arXiv:1301.6775v3 [math.NA].
URL http://arxiv.org/abs/1301.6775v3

The use of local single-pass methods (like, e.g., the Fast Marching method) has become popular in the solution of some Hamilton-Jacobi equations. The prototype of these equations is the eikonal equation related to the level-set method and applied in several applications including image processing. For this equation the methods can be applied saving CPU time and possibly memory allocation. Then, some natural questions arise: can local single-pass methods solve any Hamilton-Jacobi equation? If not, where the limit should be set? We will try to answer these questions. In order to give a complete picture, we present an overview of some fast methods available in literature and we briefly analyze their main features. We also provide some numerical tests which are intended to exhibit the limitations of the methods. We show that the construction of a local single-pass method for general Hamilton-Jacobi equations is very hard, if not impossible. Nevertheless, some special classes of problems can be actually solved, making local single-pass methods very useful from the practical point of view. Some examples taken from Shape-from-Shading models will be discussed.

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3.8 Image-Based Approaches for Photo-Realistic Rendering of Clothes

Anna Hilsmann (HU Berlin, DE)

Joint work of Hilsmann, Anna; Fechteler, Philipp; Eisert, Peter
Main reference A. Hilsmann, P.Fechteler, P. Eisert, "Pose Space Image Based Rendering," Computer Graphics Forum, 32(2):265–274, 2013.
URL http://dx.doi.org/10.1111/cgf.12046

In this talk, I presented methods for image-based rendering and modification of objects with complex appearance properties, concentrating on the example of clothes. With physical simulation methods, rendering of clothes is computationally demanding because of complex cloth drapery and shading. In contrast, the proposed methods use real images, which capture these properties and serve as appearance examples to guide complex animation or texture modification processes. Texture deformation and shading are extracted as image warps both in the spatial and in the intensity domain (Hilsmann et al 2010). Based on these warps, a pose-dependent image-based rendering method synthesizes new images of clothing from a database of pre-recorded images (Hilsmann et al. 2013). For rendering, the images and warps are parametrized and interpolated inpose-space, i.e. the space of body poses, using scattered data interpolation. To allow for appearance changes, an image-based retexturing method is proposed,which exchanges the cloth texture in an image while maintaining texture deformation and shading properties, without the knowledge of the scene geometry and lighting conditions (Hilsmann et al. 2011). Altogether, the presented approaches shift computational complexity from the rendering to an a-priori training phase. The use of real images and warp-based extraction of deformation and shading allow a photo-realistic visualization and modification of clothes, including fine details, without computationally demanding simulation of the underlying scene and object properties.

3.9 Variational Perspective Shape from Shading

Yong Chul Ju (Universität Stuttgart, DE)

Joint work of Breuß, Michael; Bruhn, Andrés

Shape from Shading (SfS) has been a classical task over decades in computer vision and enormous progress has been made with the methods of using partial differential equations in recent years. However, there is still a lack of state-of-the-art models in variational methods. In this talk, we propose a novel variational model for SfS which offers several advantages compared to existing variational approaches.

(i) It is the first variational model based on advanced camera models such as perspective projections.
(ii) As a perspective model it is the first one that directly allows to compute depth instead of estimating and integrating surface normals.
(iii) Due to the direct computation it does not require integrability constraints since it fulfils the integrability condition by construction.

This is joint work with Michael Breuß (Brandenburg University of Technology) and Andrés Bruhn (University of Stuttgart).

3.10 Segmentation in 3-D surface data

Margret Keuper (Universität Freiburg, DE)

Currently, several methods are available to reconstruct 3-D surfaces of complex scenes with a certain accuracy. However, segmentation in these scenes is not trivial. First, the data is usually not complete, i.e. we are not provided aclosed triangle mesh but rather a triangle soup with holes. Secondly, the datais degraded by recording noise resulting in reconstruction artefacts. Thirdly, the lack of fully labelled 3-D data makes it hard to learn object category specific appearance. I am going to present our most recent work on graph reduction for image segmentation and its extension to point clouds from single view RGB-D. Our method allows for a fast and accurate segmentation of large point clouds using the spectral clustering paradigm.

3.11 Data flattening: A spectral perspective

Ron Kimmel (Technion – Haifa, IL)

Joint work of Aflalo, Yonathan; Kimmel, Ron
Main reference Y. Aflalo, R. Kimmel, "Spectral multidimensional scaling," in Proc. of the National Academy of Sciences of the United States of America (PNAS), 110(45):18052–18057, 2013.
URL http://dx.doi.org/10.1073/pnas.1308708110

Mapping metric structures to the plane can be realized by multidimensional scaling methods. The input to such procedures is the set of inter-geodesic distances between points of the data we would like to map to the plane. The complexity of the input to these algorithms is quadratic in the number of inputdata points. In the talk a quasi-linear method (in space and time) was presented for that goal exploiting properties of the natural basis for this problem. Based on joint work with Yonathan Aflalo.

References

1 Y. Aflalo, and R. Kimmel. Spectral multidimensional scaling, Proc. NationalAcademy of Sciences (PNAS), 110(45):18052-18057, 2013

3.12 Efficient Detection of Deformable Objects

Iasonas Kokkinos (Ecole Centrale – Paris, FR)

Joint work of Kokkinos, Iasonas; Haithem Boussaid
Main reference I. Kokkinos, "Rapid Deformable Object Detection using Dual Tree Branch and Bound," in Proc. of the 25th Annual Conf. on Neural Information Processing Systems (NIPS'11), pp. 2681–2689, 2011.
URL http://papers.nips.cc/paper/4338-rapid-deformable-object-detection-using-dual-tree-branch-and-bound.pdf

Deformable Part Models (DPMs) play a prominent role in current object recognition research, as they allow to rigorously deal with shape variability in an object category. Still, the computational requirements of such models make them unsuitable for real-time applications.

In this talk we will see how well-known optimization techniques, such as Branch-and-Bound and the Alternating Direction Method of Multipliers (ADMM) can be used to efficiently perform inference with DPMs. Instead of evaluating the classifier score exhaustively for all part locations and scales, such techniques allow us to quickly focus on promising image locations. The core problem that we will address is how to compute bounds that accommodate part deformations; this allows us to apply Branch-and-Bound to our problem. We will then present a technique to provide quick probabilistic bounds to the individual part scores by using Chebyshev's inequality, and will finally present a decomposition technique that allows us to deal with models of complicated graph structure by employing ADMM for fast convergence. When comparing to the baseline DPM implementation of Felzenszwalb et al, we obtain exactly the same results but can perform the part combination substantially faster (yielding double up to tenfold or higher speedups); on a challenging medical shape segmentation benchmark our ADMM-based technique yields substantially better results than the previous state-of-the-art, while converging in a few seconds.

3.13 On Shape Recognition and Language

Petros Maragos (National TU – Athens, GR)

URL http://cvsp.cs.ntua.gr

Shapes convey meaning. Language is efficient in expressing and structuring meaning. The main thesis of this presentation is that by fusing shape and linguistic information shape recognition can be improved in performance and can also be enriched by adding language-based semantics. This talk focuses on two paradigms from two broad classes of moving shapes that are related to language: (1) moving handshapes from videos of sign language, and (2) multimodal gestures combining audio and visual information. In (1) we fuse shape information that consists of 2-D handshape images and their 2-D motion-position with sign linguistic information in the form of subunit sequences. In (2) we fuse 3-D shape from motion-position of gesturing hands/arms and 2-D handshapes in RGB and Depth visual channels with audio information in the form of acoustically recognized keyword sequences. In both applications the performance of shape classification or recognition significantly improves by fusing geometry with linguistic information. This is joint work with S. Theodorakis, V. Pitsikalis, A. Roussos, G. Pavlakos and A. Katsamanis. Supported by the research project "COGNIMUSE". More information, related papers and current results can be found in http://cvsp.cs.ntua.gr.

3.14 Relation between total variation and persistence distance and its application in signal processing

Gerlind Plonka-Hoch (Universität Göttingen, DE)

Joint work of Plonka-Hoch, Gerlind; Zheng, Yi
Main reference G. Plonka, Y. Zheng, "Relation between total variation and persistence distance and its application in signal processing," Manuscript, January 2014.
URL http://num.math.uni-goettingen.de/~plonka/pdfs/plonka_zheng.pdf

In this talk we establish the new notion of persistence distance for discrete signals and study its main properties. The idea of persistence distance is based on recent developments in topological persistence for assessment and simplification of topological features of data sets. Particularly, we establish a close relationship between persistence distance and discrete total variation for finite signals. This relationship allows us to propose a new adaptive denoising method based on persistence that can also be regarded as a nonlinear weighted ROF model. Numerical experiments illustrate the ability of the new persistence based denoising method to preserve significant extrema of the original signal.

3.15 Time Discrete Geodesic Paths in the Space of Images

Martin Rumpf (Universität Bonn, DE)

Joint work of Berkels, Benjamin; Effland, Alexander; Rumpf, Martin

The space of images is considered as a Riemannian manifold using the metamorphosis approach proposed by Trouvé and Younes. Via a generalization of the flow of diffeomorphism approach simultaneous transport and intensity variations are both reflected by the underlying Riemannian metric. A robust and effective variational time discretization of geodesics paths is proposed, which requires to minimize a discrete path energy consisting of a sum of consecutive image matching functionals over a set of image intensity maps and pairwise matching deformations. Under minimal regularity requirements for the input images the existence of discrete geodesic paths defined as minimizers of this variational problem is shown. Furthermore, Γ-convergence of the underlying discrete path energy to the continuous path energy is proved. This includes a diffeomorphism property for the induced transport and the existence of a square-integrable weak material derivative in space and time. A spatial discretization via finite elements combined with an alternating descent scheme in the set of image intensity maps and the set of matching deformations is presented to numerically approximate the discrete geodesic paths. Computational results underline the efficiency of the proposed approach and demonstrate important qualitative properties.

3.16 Shape distance and Shape prior

Frank R. Schmidt (Universität Freiburg, DE)

Joint work of Gorelick, Lena; Schmidt, Frank R.; Boykov, Yuri
Main reference L. Gorelick, F. R. Schmidt, Y. Boykov, "Fast Trust Region for Segmentation," in Proc. of the 2013 IEEE Conf. on Computer Vision and Pattern Recognition (CVPR'13), pp. 1714–1721, IEEE, 2013.
URL http://dx.doi.org/10.1109/CVPR.2013.224

Trust region is a well-known general approach to optimization which offers many advantages over standard gradient descent techniques. In particular, it allows more accurate nonlinear approximation models. In each iteration this approach computes a global optimum of a suitable approximation model within a fixed radius around the current solution, a.k.a. trust region. In general, this approach can be used only when some efficient constrained optimization algorithm is available for the selected non-linear (more accurate) approximation model. In this talk I present a Fast Trust Region (FTR) approach for optimization of segmentation energies with non-linear regional terms, which are known to be challenging for existing algorithms. These energies include, but are not limited to, volume constraint and Bhattacharyya distance between the observed and the target appearance distributions. In particular, I show that replacing the well-known Hamming distance with a distance that is more related to shape matching results in a robust algorithm that outperforms the classical level-set approach with respect to both accuracy and time.

3.17 Anisotropic Third-Order Regularization for Sparse Digital Elevation Maps

Carola-Bibiane Schönlieb (University of Cambridge, GB)

Joint work of Lellmann, Jan; Morel, Jean-Michel; Schönlieb, Carola-Bibiane
Main reference J. Lellmann, J.-M. Morel, C.-B. Schönlieb, "Anisotropic Third-Order Regularization for Sparse Digital Elevation Models," in Proc. of the 4th Int'l Conf. on Scale Space and Variational Methods in Computer Vision (SSVM'13), LNCS, Vol. 7893, pp. 161–173, Springer, 2013.
URL http://dx.doi.org/10.1007/978-3-642-38267-3_14

We consider the problem of interpolating a surface based on sparse data such as individual points or level lines. We derive interpolators satisfying a list of desirable properties with an emphasis on preserving the geometry and characteristic features of the contours while ensuring smoothness across level lines. We propose an anisotropic third-order model and an efficient method to adaptively estimate both the surface and the anisotropy. Our experiments show that the approach outperforms AMLE and higher-order total variation methods qualitatively and quantitatively on real-world digital elevation data.

3.18 3-D statistical face models for 2-D image analysis

William Smith (University of York, GB)

Main reference O. Aldrian, W. A. P. Smith, "Inverse Rendering of Faces with a 3-D Morphable Model," IEEE Trans. on Pattern Analysis and Machine Intelligence, 35(5):1080–1093, 2013.
URL http://dx.doi.org/10.1109/TPAMI.2012.206

Statistical face models have a long history in computer vision, including the now classical techniques of Eigenfaces, Active Shape Models and Active Appearance Models. Later, approaches such as 3-D Morphable Models attempted to capture the intrinsic features of a face (3-D shape and reflectance properties) allowing an explicit image formation model to be used in an analysis-by-synthesis framework. In this talk, I will describe recent work on obtaining training data (i.e. capturing face intrinsics) and how such models can be used to analyse 2-D images, providing a statistical route to facial shape-from-shading. Finally, I will discuss what I believe are the open questions in statistical face modelling.

3.19 Towards a design grammar

Sibel Tari (Middle East Technical University – Ankara, TR)

Joint work of Tari, Sibel; Ozkar, M.; H. Keles
Main reference H. Y. Keles, M. Özkar, S. Tari, "Weighted shapes for embedding perceived wholes," Environment and Planning B: Planning and Design, 39(2):360–375, 2012.
URL http://dx.doi.org/10.1068/b37067

A major step towards computer-aided creative design is the ability to automatically envision different parts in a whole and to continuously divide and combine. In this talk, I will review recent progress at Middle East Technical University towards a design grammar implementation. The talk will feature a couple of interrelated methods, all benefiting from the use of diffuse forms of designs computed via Screened Poisson. I will also address how new designs can be generated from older ones using mild randomization. (The talk is based on two joint works, with M. Ozkar and with H. Keles)

3.20 Semi-Lagrangian Approximation of non-Lambertian Reflectance Models for the Orthographic Shape-from-Shading Problem

Silvia Tozza (University of Rome "La Sapienza", IT)

Several advances have been made in the last ten years to improve the Shape–from–Shading model in order to allow its use on real images. The classic Lambertian model, suitable to reconstruct 3-D surfaces with uniform reflection properties, has shown to be unsuitable for other types of surfaces, for example for rough objects consisting of materials such as clay. Other models have been proposed by several authors but it is still unclear what could be the best one (if there is a best). To this end we have analyzed some models for non-Lambertian surfaces focussing our attention on Phong and Oren-Nayar models which

seem to be more flexible and accurate than other models. In particular, the first is intended to treat specular surfaces whereas the second includes diffusion reflectance terms. We present a semi-Lagrangian approximation schemes for nonlinear partial differential equations corresponding to these models, analyze their properties and compare them with the classical Lambertian model on a series of benchmarks images.

3.21 Dense Non-Rigid Shape Correspondence using Random Forests

Matthias Vestner (TU München, DE)

Since the 2000s there has been an increasing influx of work on finding and describing correspondences among 3-dimensional shapes. Due to the highly ill-posed nature of the shape matching problem, it is very unlikely that a general method will reliably find good matchings between arbitrary shapes. In this talk the correspondence problem between non-rigid shapes will be tackledvia a learning-by-examples approach. We treat the shape matching problem as a classification problem, where input samples are points on a test-shape and the output class is an element of a canonical label set, which might e.g. coincide with one of the shapes in the training set. As a classifier we choose the random forest paradigm, that can in general be built upon any parametrizable feature descriptor. As a particular instance of such a descriptor the Wave Kernel signature will be presented. In order to get rid of artifacts caused by symmetry properties of the considered shapes further a regularizer will be introduced.

3.22 Morphological amoebas and image segmentation

Martin Welk (UMIT – Hall in Tirol, AT)

Morphological amoebas are a class of image-adaptive structuring elements which can be used in connection with various morphological filters. Amoeba-based filters have interesting connections to partial differential equations used in image processing; for example, amoeba median filtering is closely related to the self-snakes PDE [6, 5, 2]. Based on this observation, also an active contour algorithm can be devised that uses amoeba median filtering to evolve the level set function of a contour [5, 4, 3].

In the talk results on this segmentation approach were summarised. Additionally, preliminary results of recent work directed at extracting additional information on texture from the intrinsic structure of amoebas were presented [1].

References

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3 M. Welk. Analysis of Amoeba Active Contours. Technical Report, http://arXiv.org/abs/1310.0097
4 M. Welk. Relations between amoeba median algorithms and curvature-based PDEs. In A. Kuijper et al., eds., Scale-Space and Variational Methods in Computer Vision, LNCS 7893, 392–403, Springer, Berlin, 2013.
5 M. Welk. Amoeba active contours. In A. Bruckstein et al., eds., Scale Space and Variational Methods in Computer Vision. LNCS 6667, 374–385, Springer, Berlin, 2012.
6 M. Welk, M. Breuß, O. Vogel. Morphological amoebas are self-snakes. Journal of Mathematical Imaging and Vision, 39:87–99, 2011.

3.23 Statistical Modeling of 3-D Human Face Shapes

Stefanie Wuhrer (Universität des Saarlandes, DE)

Joint work of Brunton, Alan; Bolkart, Timo; Wuhrer, Stefanie
Main reference A. Brunton, T. Bolkart, S. Wuhrer, "Multilinear Wavelets: A Statistical Shape Space for Human Faces," arXiv:1401.2818v1 [cs.CV], 2014.
URL http://arxiv.org/abs/1401.2818v1

Accurate reconstruction of face shape is important for applications such as tele-presence and gaming. Such a reconstruction problem can be solved efficiently and in the presence of noise with the help of statistical shapemodels that constrain the shape of the reconstruction. In this talk, a statistical model to represent 3-D human faces in varying expression is discussed, which decomposes the surface of the face using a wavelet transform, and learns many localized, decorrelated multilinear models on the resulting coefficients. The localized and multi-scale nature of this model allows for recovery of fine-scale detail while retaining robustness to severe noise and occlusion, and is computationally efficient and scalable.

3.24 Shape Compaction

Hao Zhang (Simon Fraser University – Burnaby, CA)

Joint work of Zhang, Hao; Hu, Ruizhen; Li, Honghua Li; Alhasheem, Ibraheem; Shamir, Ariel; Cohen-Or, Daniel
Main reference H. Li, I. Alhashim, H. Zhang, A. Shamir, D. Cohen-Or, "Stackabilization," ACM Trans. on Graphics (Special Issue of SIGGRAPH Asia), 31(6), Article 158, 2012.
URL http://doi.acm.org/10.1145/2366145.2366177
URL http://www.computer-graphics.cn/~hh/projects/stackem/

Compact shape *representations*, e.g., compression, is a well-studied problem. We are interested in compaction at the shape *configuration* level. The termshape configuration refers to how a shape, real or conceptual, is physically modelled (e.g., in terms of design and composition of its parts) and spatially arranged (e.g., in terms of shape/part positioning and possibly in relation to other shapes). The required storage is the actual physical space the shape configuration occupies. Compact shape configurations can save valuable space in industrial settings, e.g., for storage, shipping, printing, etc., leading to cost reduction. The key difference to compaction at the representation level is that by changing shape configurations, we allow a given shape to undergo significant changes, which are certainly beyond a close geometric approximation. For example, we may change how a shape is decomposed and assembled

so it can be better folded or alter its geometry so that it can be more compactly stacked with other shapes. Compact shape configurations can be generated by either re-modeling or re-arranging the parts within one shape or changing the inter-shape spacial relations of a set shapes. In this talk, I will pose three new problems: stackabilization, pyramidaliztion, and foldablization, and present our progress on solving them.

3.25 Shape descriptors/measures

Jovisa Zunic (University of Exeter, GB)

Shape is an object property which has a big discrimination capacity. This is because the shape allows many numerical characterisations. Some of these numerical characterisations relate to the validation of certain intuitively clear shape properties (usually called shape descriptors) e.g. shape convexity, shape elongation, shape compactness, etc. Methods for numerical validations, of such properties (i.e. shape descriptors) are called the shapemeasures. Some of shape descriptors have already assigned multiple shapemeasures (convexity, compactness, etc). Since shape descriptors have an intuitively clear meaning, the behaviour of the measures, assigned to them, can be predicted to some extent, which enables a priory estimate of how a certain measure fits to the task performed. The problems is that the number of shape descriptors is not large, e.g. comparing with the number of generic shape descriptors (usually do not have a clear geometric interpretation). In this talk, some ideas/results about how to overcome such a drawback and how to expand the applicability of shape/descriptors will be presented.

4 Working Groups

4.1 Summary of Break-out Session

Yong Chul Ju (Universität Stuttgart, DE)
Stefanie Wuhrer (Universität des Saarlandes, DE)

During the break-out session, five small groups discussed the following topics with the goal to identify the most pressing research questions in these areas: intrinsic structure, (co)segmentation, shape from shading, models for deformable shapes, and face deformation models. Here, we briefly summarise the outcomes of the discussions.

Intrinsic Structure: Efficient shape representations play an important role for many tasks in computer vision, such as the matching problem or object recognition. However, simple geometric features of an object, in general, are not always distinctive enough to capture important structures, such as the distortions of non-rigid objects. The study of the self-similarity of an object under deformations that preserve either the extrinsic or the intrinsic geometry of the object may help to derive efficient shape representations. This observation leads to the main question of how to encode the self-similarity of an object as shape descriptor.

(Co)Segmentation: Co-segmentation is the task of segmenting a set of given images or 3-D shapes into corresponding parts. Since it is extremely difficult to have a perfect match of an object between one or more pairs of input images, e.g. due to self-occlusion and shading, one has to almost always deal with missing correspondences. As a consequence, incorporating partial correspondences is an essential step to tackle the (co)segmentation problem from several input images successfully.

Shape from Shading (SfS): Although SfS has been one of the key problems in computer vision, there is still no unified SfS model framework that can combine several modelling components and parameters. Specifically, it remains a challenge to combine non-Lambertian and Lambertian models and to formulate one equation composed of ambient, Lambertian and specular parts. In order to further develop new models and solutions, a carefully devised unified framework would be a valuable tool. In addition, most work related to SfS considers only a single greyscale input image. However, exploiting colour information for SfS would be interesting, as most greyscale images are also acquired from colour images nowadays.

Models for deformable shapes: In order to model deformable shapes, mimicking the behaviour of an amoeba, a unicellular organism, is a basic and effective tool. However, there is still no satisfying mathematical description of how amoebas move in the plane. So finding such a description is the first step toward further development in the field. In addition, interpenetration effects in real world situations caused by interweaving or distortions, e.g. in the overlapping area on the human face, remain extremely challenging. There is a definite need to handle these situations.

Face deformation models: As a special case of deformable shapes, statistical face deformation models draw much attention, since they have numerous potential applications ranging from gaming to surveillance systems. However, the accuracy of statistical models is currently not sufficient to satisfy requirements such as the high geometric and visual accuracy needed for movie production. As a result, there is a definite need to obtain an accurate statistical model that can integrate all critical aspects from geometric and colour information to other appearance information at high resolution and with high accuracy.

Participants

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Report from Dagstuhl Seminar 14081

Robots Learning from Experiences

Edited by

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Abstract

This report documents the programme and the outcomes of Dagstuhl Seminar 14081 "Robots Learning from Experiences". The report begins with a summary comprising information about the seminar topics, the programme, important discussion points, and conclusions. The main body of the report consists of the abstracts of 25 presentations given at the seminar, and of four reports about discussion groups.

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1 Executive Summary

Anthony G. Cohn
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Topics and Motivation

The ability to exploit experiences is an important asset of intelligent beings. Experiences provide a rich resource for learning, solving problems, avoiding difficulties, predicting the effects of activities, and obtaining commonsense insights. Current robots do not in general possess this ability, and this is a decisive reason for the often perceived "lack of intelligence" of current robotic systems: they repeat mistakes, do not learn to anticipate happenings in their environment, and need detailed instructions for each specific task.

> Consider an everyday task of a service robot, such as grasping a cup from a cupboard and bringing it to a person sitting at a table. This task may occur in many variations and under unpredictable circumstances. For example, persons may sit at different sides of a table, a direct path to the table may be blocked, the table may be cluttered with various objects, hot water may be ready or not, the cup on the shelf may be upside-down, etc. It is clearly infeasible to provide the robot with precise instructions for all contingencies at design time or to specify tasks with highly detailed instructions

for each particular concrete situation which may arise. Hence without such knowledge, robot behaviour is bound to lack robustness if the robot cannot autonomously adapt to new situations.

How would the robot, for example, avoid pouring coffee into an upside-down cup? Based on experiences with multiple pouring actions, the robot will have formed a conceptualisation of all concomitant circumstances of successful pouring, for example to pour into a "container". The robot may not know the name of this conceptualisation but will know that it must be open on top, hollow, empty, etc. Similarly, the robot may have encountered upside-down objects before and hence be able to conceptualise the corrective action of turning an object to make it a usable container.

This seminar has brought together experts and scholars from the robotics, learning, and knowledge representation communities to discuss current approaches to make robots learn from experiences. Emphasis was on the representation of real-world experiences and on exploiting experiences for autonomous acting in a changing or partially unknown environment.

2 Table of Contents

3 Seminar Overview

Programme

The seminar was attended by 41 participants. Based on abstracts submitted before, the organizers had proposed a tentative programme and distributed it to all participants. The programme was slighly adapted during the seminar, its final version is shown below. The talks were presented as shown in the schedule (Fig. 1). Thanks to the speakers, there was sufficient time for discussion after the talks, and the time frame could be kept without difficulties.

The invited participants included delegates from several EU projects that all share a strong focus on the workshop topics (RACE, STRANDS, Co-Friends, RobotHearth, RoboHow, GeRT, XPERIENCE). This choice was aimed at maximizing the sharing of knowledge and results across those projects both through presentations and, more importantly, though informal discussions.

	Monday		Tuesday		Wednesday		Thursday		Friday
08:45	Organizers, all	Opening, short presentations	Luc De Raedt KU Leuven	Statistical Relational Learning for Robotics and Computer Vision	Ivan Bratko Univ. of Ljubljana	Discovery of Abstract Notions by a Robot	Carme Torras UPC – Barcelona	Robot manipulation in human environments: Challenges for learning	Discussion Springer Book
09:15	Bernd Neumann Univ. of Hamburg	Introduction to seminar topic			Krishna Sandeep Reddy Dubba Univ. of Leeds	Scene layout conceptualization and recognition using graphs			
09:45	Coffee								
10:15	Michael Beetz Univ. of Bremen	Experience-based Learning for Bayesian Cognitive Robotics	Michael Zillich TU Wien	Project report STRANDS	Martin Günther Univ. of Osnabrück	Context-aware semantic object mapping for plan execution	Manfred Hild Humboldt University Berlin	Self-Exploration of Autonomous Robots Using Attractor-Based	Reports from discussion groups
10:45			Jianwei Zhang Univ. of Hamburg	Project Report RACE	Vaclav (Vasek) Hlavac Czech TU in Prague	Dual-arm manipulation with clothes, lessons from CloPeMa project.	Sebastian Stock Univ. of Osnabrück	Towards an integrated hierarchical planner for complex robot tasks	
11:15	Pierre-Yves Oudeyer INRIA – Bordeaux	Developmental robotics: lifelong learning and the morphogenesis of developmental structures	Federico Pecora Univ. of Orebro	Reasoning about Learned Knowledge for Robots: the Next Big Challenge for AI?	Laurent Orseau AgroParisTech – Paris	Beyond the traditional agency framework	Sebastian Rockel Univ. of Hamburg	Beyond state-of-the-art Planning: A Survey of Imaginary Planning	
11:45			All	Collecting discussion topics	All	Collecting discussion topics	Muralikrishna Sridhar Univ. of Leeds +	Scene Understanding from Videos	Wrapping up by organizers
12:15	Lunch								
14:00	Luc Steels Free Univ. of Brussels	Robot tutoring	Marek S. Kopicki Univ. of Birmingham	Learning to generalise grasps to novel objects	Excursion, hike		Discussion groups		Departure
14:30	Richard Bowden Univ. of Surrey	Learning by Imitation	Lorenzo Jamone TU Lisboa	Autonomous Online Learning of Sensori-Motor Internal Models in Humanoid Robots					
15:00	Ales Leonardis Univ. of Birmingham	Compositional hierarchies for learning visual representations and building knowledge from experience	Sven Behnke Univ. of Bonn	Manipulation Skill Learning for Cognitive Service Robots					
15:30	Coffee								
16:00	Ralf Möller TU Hamburg-Harburg	Location Prediction Based on Mobility Patterns in Location Histories	Alexandre Bernardino TU Lisboa	Co-Development of Visuo-Motor Structures			Discussion groups		
16:30	Francois Bremont INRIA - Sophia Antipolis	Scene understanding for Activity Monitoring	Jure Zabkar Univ. of Ljubljana	Sensorimotor memory: the representation, learning and inference					
17:00	Luis Seabra Lopes Univ. of Aveiro	Conceptualization of objects and activities for open-ended learning in robotics	Emre Ugur Univ. of Innsbruck	Skill development through affordance-based bootstrapping					
17:30	All	Collecting discussion topics	All	Collecting discussion topics					
18:00	Dinner								

Figure 1 Schedule of the seminar.

Seminar Introduction

At the beginning of the opening session, all participants introduced themselves shortly and indicated which special interests they had in the seminar. Bernd Neumann then introduced to the seminar topic. He first gave some examples of what robots could learn from experiences and then pointed out several open issues which should hopefully be addressed and maybe clarified during the seminar. In particular, he addressed knowledge representation issues regarding formalisms and tools. He also pointed out integration issues arising, for example, from divergent requirements of robotic components regarding a common ontology. Another important issue is modelling, in particular when using the standardized language OWL. As yet, there is no standardized support for compositional hierarchies and constraints, among others.

Discussions

Each day, discussion topics were collected for extended treatment in discussion groups. The topics were clustered, and the following discussion sessions were arranged reflecting the interest of the participants:

Session 1a and 1b

- How to construct a good Ontology?
- Representations bridging the gap between high and low level
- Can we learn anything suitable to be used by higher levels?
- Can we use high-level knowledge to influence the low level?
- Semantic vs. low-level information
- Where/how should uncertainty be dealt with in learning robots?
- Computer Vision in Robotics

Session 2

- Learning strategies
- Domain adaptation, knowledge transfer
- What is the role of affordances in robot learning, control and planning?
- Weakly supervised learning
- Learning over long periods
- One-shot learning vs. statistical learning

Session 3

- Setting up learning experiments
- Collecting datasets, robot tasks, challenges
- Performance metrics for learning in Robotics

Session 4a and 4b

- Should we take a system perspective on the above questions?
- Theoretical framework for learning agents
- Selfmodifying agents, representations vs. processes
- Learning commonsense, metaknowledge

The points of views and prevailing opinions voiced in the discussion sessions were collected by rapporteurs and presented in a plenary session on Friday morning.

Book Publication

Participants discussed whether refereed seminar contributions should be collected for a book or special issue of a journal. The majority showed preference and interest in contributing to a book, for example in the Springer LNCS series. It was agreed that the seminar organizers would explore both possibilities.

Conclusions

The questionnaires distributed by the Dagstuhl organization showed that the participants appreciated the organization of the seminar, the contributions of the speakers and the insights gained in the discussions. Hopefully, the seminar has helped to pave the way for a next generation of cognitive robotic systems.

4 Overview of Talks

4.1 Experience-based Learning for Bayesian Cognitive Robotics

Michael Beetz (Universität Bremen, DE)

Bayesian cognitive robotics is a novel paradigm for the knowledge-enabled control of autonomous robots. The paradigm presumes that one of the most powerful ideas to equip robots with comprehensive reasoning capabilities is the lifelong autonomous learning of joint probability distributions over robot control programs, the behavior they generate and the situation-dependent effects they bring about. Having learned such probability distributions from experience, a robot can make predictions, diagnoses and perform other valuable inference tasks in order to improve its problem-solving performance. In this talk, I will present our ongoing research efforts in investigating the realization and the potential impact of Bayesian cognitive robotics by 1. presenting the design of plans facilitating Bayesian cognitive robotics, 2. explaining how the plans collect experiences in performing human-scale manipulation activities, and 3. showing how robots can learn realistic first-order joint probability distributions over plans, their behavior, and the effects they cause.

4.2 Manipulation Skill Learning for Cognitive Service Robots

Sven Behnke (Universität Bonn, DE)

Service robots need to be equipped with sufficient cognitive abilities to perceive their surroundings and to plan their actions. They also need to learn from experience. At University of Bonn, we developed cognitive service robots that integrate robust mobility, object manipulation and intuitive multimodal interaction with human users [1, 2]. In the talk, I report on the learning of manipulation skills. This is based on robust perception of the manipulated objects by laser scanners and RGB-D sensors. We learn models of object geometry and appearance from moving sensors and track them in real time [3]. By means of deformable registration between models and the current RGB-D view, our robot can generalize manipulation skills to novel object instances [4]. For learning manipulation skills, we developed an interactive approach that combines the advantages of reinforcement and imitation learning in a single coherent framework [5]. This method is used to learn the grasping of objects. Goal-directed representation of motion facilitates segmentation of motion sequences into actions and the transfer of motions to new situations [6]. We extend our approach to action sequences [7] and to action hierarchies in a MAXQ hierarchical reinforcement learning formulation in continuous state spaces using Gaussian Process Regression [8]. We demonstrate the ability to efficiently learn solutions to complex tasks in a box stacking scenario. Finally, I report on recent advanced in semantic mapping using object class segmentation of RGB-D images by random forests and 3D SLAM fusion [9] or discriminative superpixel CRF learning [10].

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7 K. Gräve and S. Behnke: Learning Sequential Tasks Interactively from Demonstrations and Own Experience. Intelligent Robots and Systems (IROS), IEEE/RSJ International Conference on, Tokyo, Japan, 2013.
8 K. Gräve and S. Behnke: Bayesian Exploration and Interactive Demonstration in Continuous State MAXQ-Learning. Robotics and Automation (ICRA), IEEE International Conference on, Hong Kong, 2014.
9 J. Stückler, B. Waldvogel, H. Schulz, and S. Behnke: Dense Real-Time Mapping of Object-Class Semantics from RGB-D Video. Journal of Real-Time Image Processing, 2014.
10 A. C. Müller and S. Behnke: Learning Depth-Sensitive Conditional Random Fields for Semantic Segmentation of RGB-D Images. Robotics and Automation (ICRA), IEEE International Conference on, Hong Kong, 2014.

4.3 On the Co-development of Visuomotor Structures: How to Create an Artificial Retina.

Alexandre Bernardino (Technical University – Lisboa, PT)

Joint work of Ruesch, Jonas; Ferreira, Ricardo; Bernardino, Alexandre
Main reference J. Ruesch, R. Ferreira, A. Bernardino, "A computational approach on the co-development of artificial visual sensorimotor structures," Adaptive Behavior, 21(6):452–464, December 2013.
URL http://dx.doi.org/10.1177/1059712313492176

Many simple biological systems are able to survive and exhibit advanced behavior with very limited neuronal resources due to very adapted sensorimotor systems to their particular environment. Following the same paradigm, and inspired in some solutions found in biological systems, we are working to provide robots with highly optimized sensorimotor processing systems through the joint optimisation of their different subsystems. Having small low-cost embedded robots operating in the real world with reduced computational resources is a necessary step towards the large- scale deployment of robots to perform distributed tasks and/or operate in barely accessible places to execute tasks otherwise impossible for humans. In this talk we present an approach for co-development of sensori-motor structures based on the minimisation of a prediction error under sparsity inducing criteria. We focus particularly

on the visuo-motor system an show how to self-organize the retina morphology and the topology of the motor space (motor-primitives) of an agent that collects experiences (pre- and post-action stimuli) on a certain environment. We show that biologically resembling structures can be developed from realistic natural stimuli with very few initial assumptions.

4.4 Learning by Imitation

Richard Bowden (University of Surrey, GB)

We pose learning by imitation as a weakly supervised learning approach where human action or noisy annotation provides weak supervision to the learning process. Trying to identify consistent visual features that correspond to an action or classification then becomes a data mining process. This talk will briefly outline 2 approaches to learning by example. In the first example we will discuss how pre-attentive vision modelled by low level filter banks can provide regressed control signals and scenario classification for an autonomous vehicle. In the second example we will show how standard datamining tools can be used in an active learning framework to provide image and video classification with equal or superior performance to state-of-the-art batch learning approaches using significantly less data.

4.5 Discovery of Abstract Concepts by a Robot

Ivan Bratko (University of Ljubljana, SI)

Joint work of Bratko, Ivan; Leban, Gregor
Main reference I. Bratko, "Autonomous discovery of abstract concepts by a robot," in Proc. of the 10th Int'l Conf. on Adaptive and Natural Computing Algorithms (ICANNGA'11), LNCS, Vol. 6593, pp. 1–11, Springer, 2011.
URL http://dx.doi.org/10.1007/978-3-642-20282-7_1

How could a robot, on its own, discover abstract notions such as a general concept of a tool? In this talk, I will describe one possible approach to this, and present experiments in autonomous discovery of abstract concepts in a robotic domain. The setting involves an autonomous robot performing tasks in its world, collecting data and learning predictive theories about its world. In particular, we are interested in the robot's inventing new abstract concepts that enable the simplification of the robot's current theory about the world. Such newly introduced concepts, sometimes called insights, improve the robot's hypothesis language and thus make the further learning more effective. Examples of insights are discoveries of concepts like mobility, obstacle, stability, etc. It should be noted that these concepts are not explicitly present in the robot's sensory observations, which makes the use of machine learning techniques more difficult. A particular challenge is to make the robot discover functional roles of objects in solving robot manipulation tasks. In an experiment in robot's learning from its plans to solve concrete tasks, the concept of a tool was discovered. Our approach employs machine learning in logic (Inductive Logic Programming) with predicate invention.

4.6 Scene Understanding for Activity Monitoring

Francois Bremond (INRIA Sophia Antipolis – Méditerranée, FR)

Scene understanding is the process, often real time, of perceiving, analyzing and elaborating an interpretation of a 3D dynamic scene observed through a network of sensors (e.g. video cameras). This process consists mainly in matching signal information coming from sensors observing the scene with models which humans are using to understand the scene. Based on that, scene understanding is both adding and extracting semantic from the sensor data characterizing a scene. This scene can contain a number of physical objects of various types (e.g. people, vehicle) interacting with each others or with their environment (e.g. equipment) more or less structured. The scene can last few instants (e.g. the fall of a person) or few months (e.g. the depression of a person), can be limited to a laboratory slide observed through a microscope or go beyond the size of a city. Sensors include usually cameras (e.g. omni- directional, infrared), but also may include microphones and other sensors (e.g. optical cells, contact sensors, physiological sensors, radars, smoke detectors). Scene understanding is influenced by cognitive vision and it requires at least the melding of three areas: computer vision, cognition and software engineering. Scene understanding can achieve five levels of generic computer vision functionality of detection, localization, tracking, recognition and understanding. But scene understanding systems go beyond the detection of visual features such as corners, edges and moving regions to extract information related to the physical world which is meaningful for human operators. Its requirement is also to achieve more robust, resilient, adaptable computer vision functionalities by endowing them with a cognitive faculty: the ability to learn, adapt, weigh alternative solutions, and develop new strategies for analysis and interpretation. In this talk, we will discuss how scene understanding can be applied to Home Care Monitoring.

4.7 Statistical Relational Learning for Robotics and Vision

Luc De Raedt (KU Leuven, BE)

Agents need to reason and learn about the world before they can select the right actions to perform. The world is inherently relational, that is, there exist multiple objects as well as relationships that hold amongst them and there is often knowledge available about the world that can be taken into account. But traditional approaches to robotics and computer vision have difficulties in handling such relations and background knowledge. However, the new field of statistical relational learning tackles this problem by integrating probabilistic models with expressive logical representations and machine learning. In this talk, I shall introduce statistical relational learning [2, 5] (SRL) through a number of techniques and I shall illustrate their use on a number of applications related to robotics, vision and natural language processing. More specifically, I shall introduce the relational representations that underlie SRL, show how they allow one to deal with structured environments, with a variable number of objects and relations as well as with background knowledge. I shall then continue to show how probabilistic and kernel-based methods can be extended to deal with such

relational representations in order to learn and reason about the environment. Covered techniques will include Problog, a probabilistic extension of the logic programming language Prolog [3], and kLog, a language for relational learning with kernel-based methods. These techniques shall then be illustrated on some example problems from computer vision, such as recognizing configurations of houses [1], from activity recognition, where activities of daily life can be recognized from sensory information [6], from playing massive multiplayer online games such as Travian [9], where models can be learned to predict future actions and events, and from robotics, where one can use SRL techniques to track occluded objects and reason about affordances in multi-object manipulation tasks [7, 8].

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4.8 Conceptualizing Static and Dynamic Scenes

Krishna Sandeep Reddy Dubba (University of Leeds, GB)

Joint work of Dubba, Krishna Sandeep Reddy; de Oliveira, Miguel; Lim,Gi Hyun; Kasaei, Hamidreza; Lopes, Luis Seabra; Tome, Ana; Cohn, Anthony G.; Hogg, David
Main reference K. S. R. Dubba, M. de Oliveira, G. Lim, L. Lopes, A. G. Cohn, D. Hogg, "Grounding Language in Perception for Scene Conceptualization in Autonomous Robots," In Proc. of the AAAI Spring Symposium Series 2014, to appear.
URL http://www.comp.leeds.ac.uk/scsksrd/QRR_AAAI.pdf

In order to behave autonomously, it is desirable for robots to have the ability to use human supervision and learn from different input sources (perception, gestures, verbal and textual descriptions etc). In many machine learning tasks, the supervision is directed specifically

towards machines and hence is straight forward clearly annotated examples. But this is not always very practical and recently it was found that the most preferred interface to robots is natural language. Also the supervision might only be available in a rather indirect form, which may be vague and incomplete. This is frequently the case when humans teach other humans since they may assume a particular context and existing world knowledge. We explore this idea here in the setting of conceptualizing objects, scene layouts and environment activities. Initially the robot undergoes training from a human in recognizing some objects in the world and armed with this acquired knowledge it sets out in the world to explore and learn more higher level concepts like static scene layouts and environment activities. Here it has to exploit its learned knowledge and ground language into perception to use inputs from different sources that might have overlapping as well as novel information. When exploring, we assume that the robot is given visual input, without explicit type labels for objects, and also that it has access to more or less generic linguistic descriptions of scene layout. Thus our task here is to learn the spatial structure of a scene layout and simultaneously visual object models it was not trained on. In this work [1], we present a cognitive architecture and learning framework for robot learning through natural human supervision and using multiple input sources by grounding language in perception.

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4.9 Context-aware Semantic Object Mapping for Plan Execution

Martin Guenther (Universität Osnabrück, DE)

Joint work of Guenther, Martin; Ruiz-Sarmiento, José Raúl; Stock, Sebastian; Hertzberg, Joachim

A service robot that creates and executes plans involving objects in its environment needs a semantic map of those objects and places. Such a map needs to be continually updated with new object recognition results, which may be noisy and incomplete. A key idea of this talk is that the basic object recognition results can be improved by exploiting the rich context between the objects. For example, once a monitor has been detected, the probability of an elongated object in front of it being a keyboard increases. We model these context relations as a Conditional Random Field.

We also present first steps towards a more active semantic perception system: Given a partially recognized scene, ontological knowledge about spatial layouts can be used to hypothesize areas where undetected task-relevant objects are expected. By querying the CRF for the most likely locations of undetected objects, we can plan actions to observe these areas by moving the robot to a different position or by moving occluding objects.

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4.10 Developmental Learning of Sensori-Motor Internal Models in Humanoid Robots

Lorenzo Jamone (Technical University – Lisboa, PT)

Joint work of Jamone, Lorenzo; Brandao, Martim; Natale, Lorenzo; Hashimoto, Kenji; Sandini, Giulio; Takanishi, Atsuo; Endo, Nobustuna; Metta, Giorgio; Nori, Francesco; Damas, Bruno; Santos-Victor, José

Main reference L. Jamone, M. Brandao, L. Natale, K. Hashimoto, G. Sandini, A. Takanishi, "Autonomous online generation of a motor representation of the workspace for intelligent whole-body reaching," Robotic and Autonomous Systems, 64(4):556–567, April 2014.

URL http://dx.doi.org/10.1016/j.robot.2013.12.011

The future of humanoid robots is to become efficient helpers for humans, both in the execution of everyday tasks and in the accomplishment of tedious and dangerous works. Driven by this vision, researchers have been challenged to design more and more complex robots, that show an increasing number of degrees of freedom and sensors [1, 2]; these robots should be able to cope with the unstructured environment in which humans daily live and act. In particular, it would be desirable that robot behaviors become autonomous (not requiring the supervision of a human expert) and flexible (applicable to different situations and contexts). However, as robots become more complex, building the analytical models needed for robot control is turning more and more difficult and time-consuming. Moreover, the lack of knowledge of certain hard to measure physical parameters and the existence of highly non-linear physical interactions, makes it infeasible to obtain adequate and accurate models for such kind of systems [3]; as a consequence, resorting to modern machine learning techniques is becoming a more and more popular way to provide these complex robots with the necessary representation capability (see [4] for a recent survey). I will present some of the results I obtained during the last five years in providing humanoid robots with the ability to learn sensori-motor internal models (to achieve different motor skills) i) autonomously and ii) incrementally during the goal-directed exploration of the environment. The approach I have been following focuses on some distinctive aspects:

- life-long continuous learning (accounting for both gradual and abrupt modifications in the system);

- goal-directed exploration of the environment (i.e. learning a general model by trying to accomplish specific tasks);
- developmental framework (the acquisition of a motor skill may allow to gather data to learn a new motor skill);
- bio-inspired (human-inspired) learning and control strategies.

I will discuss why goal-directed exploration is beneficial [5], and how suggestions from biology can help to build better robotic systems. I will sketch a developmental path in which a robot starts from basic visual perception to finally achieve goal-directed visually-guided locomotion and intelligent whole- body reaching capabilities, including the ability to reach with tools. Namely, first the robot learns how to the control the neck [6] and eyes to fixate targets in the environment, then it starts learning arm reaching [7] (also using different tools [9]), then it builds incrementally a representation of its own reachable space [8], and finally it exploits this knowledge to perform whole-body reaching [10] and goal-directed walking [11], that are seen as ways to maximize the reachability of visually detected objects. Results obtained on different humanoid robots (namely, James [12], Kobian [2] and iCub [1]) will be presented.

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4.11 Learning to Generalise Grasps to Novel Objects.

Marek S. Kopicki (University of Birmingham, GB)

Joint work of Kopicki. M.; Detry R.; Schmidt F.; Borst C.; Stolkin R.; Wyatt J.L.
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Generalising grasps to novel objects is an open problem in robotics. In this talk I will present a method that can learn grasps for high degree of freedom robots that generalise to novel objects, given as little as one demonstrated grasp. The method is potentially more general and can be used not only in grasping, but also in any kind of robotic applications that involve robot body-environment/object spatial relations. The example could be dexterous manipulation, manipulation of deformable objects, walking robots, etc. During grasp learning two types of probability density are learned that model the demonstrated grasp. The first density type (the contact model) models the relationship of an individual robot link to a local object feature at its neighbourhood. The second density type (the robot configuration model) models the whole robot configuration which is preferable for a particular grasp type. When presented with a new object, many candidate grasps are generated, and a grasp is selected that maximises the product of these densities. The experimental results show successful grasp transfers to novel objects performed on two different robots with different multi-finger hands. The experiments include cases where the robot has only partial information about the object shape and other physical properties.

4.12 Compositional Hierarchies for Learning Visual Representations and for Building Knowledge from Experiences

Ales Leonardis (University of Birmingham, GB)

Building knowledge from experiences is one of the most important capabilities of intelligent artificial systems. This requires proper structures and mechanisms that enable efficient learning, retrieval, and, when necessary, modification and augmentation of the acquired knowledge. Recently, it has become increasingly clear that new approaches are needed to tackle these problems and there have been several indications that possible solutions should be sought in the framework of hierarchical architectures. Among various design choices related to hierarchies, compositional hierarchies show a great promise in terms of scalability, real-time performance, efficient structured on-line learning, shareability, and knowledge transfer. In my talk I will first present our work on compositional hierarchies for learning visual representations and then present some ideas towards generalizing the proposed approach to other modalities and to building knowledge from experiences.

4.13 Location Prediction Based on Mobility Patterns in Location Histories

Ralf Moeller (TU Hamburg-Harburg, DE)

Main reference J. Lüthke, "Location Prediction Based on Mobility Patterns in Location Histories," Master's theis, Hamburg University of Technology, September 2013.
URL http://www.sts.tuhh.de/pw-and-m-theses/2013/luethke13.pdf

Human individuals generally tend to follow several habits during the course of the day. This fact intuitively allows predicting human behavior to a certain degree based on previous observations. A generic algorithm for dynamic location prediction that uses kernel density estimation and quadratic optimization is devleoped and analysed in this presentation. The algorithm was implemented and tested in a large scale environment using mobility traces of taxis. The test results clearly indicate that the algorithm can extract and exploit patterns in the data to predict future locations. For instance, the algorithm achieves an accuracy better than 1000m in approximately 32% of the executed tests using a prediction interval of six minutes. Moreover, in 13% of these tests the prediction error is smaller than 500m. In addition, the test results show that the algorithm is able to estimate the reliability of its predictions with an accuracy of up to 98.75%. As expected, the test results also clearly demonstrate that the prediction capability of the algorithm strongly depends on the properties of the given location data and the underlying stochastic process. We conjecture that the kind of location prediction we present can be adapted to be applicable also in the small scale, i.e., in cases where robots have to directly interact with humans, e.g., for carrying out service tasks.

4.14 Beyond the Traditional Agency Framework

Laurent Orseau (AgroParisTech – Paris, FR)

Joint work of Orseau, Laurent; Ring, Mark
Main reference L. Orseau, M. Ring, "Space-Time Embedded Intelligence. Artificial General Intelligence," in Proc. of the 5th Int'l Conf. on Artificial General Intelligence (AGI'12), LNCS, Vol. 7716, pp. 209–218, Springer, 2012.
URL http://dx.doi.org/10.1007/978-3-642-35506-6_22

In the traditional theoretical framework for dealing with agents, as used in Reinforcement Learning for example, an agent and an environment are put in interaction, but they are considered to be two completely separate entities. In particular, this implies that the computer of the agent is "immortal", along with its source code and memory. Although this is convenient for most purposes, this framework is actually inaccurate and can lead to wrong decisions from an autonomous and intelligent agent. We build several frameworks in order to study some consequences of making the agent being a part of the environment, where the latter can modify directly either the memory or the source code of the former. We conclude by proposing what we call the Space-Time Embedded framework, where the agent can not only be modified by the environment but is also computed by it, and we give a definition of intelligence in this framework.

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4.15 Developmental Robotics: Lifelong Learning and the Morphogenesis of Developmental Structures

Pierre-Yves Oudeyer (INRIA – Bordeaux, FR)

Joint work of Oudeyer, Pierre-Yves; Kaplan, Frédéric; Baranes, Adrien; Hafner, V.; Nguyen, Mai; Stulp, Freek; Gottlieb, J.; Lopes, Manuel

Main reference P.-Y. Oudeyer, A. Baranes, F. Kaplan, "Intrinsically Motivated Learning of Real World Sensorimotor Skills with Developmental Constraints," in G. Baldassarre, M. Mirolli, eds., Intrinsically Motivated Learning in Natural and Artificial Systems, Springer, 2013; authors' pre-print available at HAL (hal-00788611).

URL http://dx.doi.org/10.1007/978-3-642-32375-1_13

URL http://hal.inria.fr/hal-00788611

Developmental robotics studies and experiments mechanisms for autonomous life-long learning of skills in robots and humans. One of the crucial challenges is due to the sharp contrast between the high-dimensionality of their sensorimotor space and the limited number of physical experiments they can make within their life-time. This also includes the capability to adapt skills to changing environments or to novel tasks. To achieve efficient life-long learning in such complex spaces, humans benefit from various interacting developmental mechanisms which generally structure exploration from simple learning situations to more complex ones. I will present recent research in developmental robotics that has studied several ways to transpose these developmental learning mechanisms to robots. In particular, I will present and discuss computational mechanisms of intrinsically motivated active learning, which automatically select training examples [4, 5], or tasks through goal babbling [2], of increasing complexity, and their interaction with imitation learning [3]„ as well as maturation and body growth where the number of sensori and motor degrees-of-freedom evolve through phases of freezing and freeing [1, 6]. I will discuss them both from the point of view of modeling sensorimotor and cognitive development in infants and from the point of view of technology, i.e. how to build robots capable to learn efficiently in high-dimensional sensorimotor spaces.

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4.16 Reasoning about Learned Knowledge for Robots: the Next Big Challenge for AI?

Federico Pecora (University of Örebro, SE)

Joint work of Pecora, Federico; Konecny, Stefan; Mansouri, Masoumeh; Saffiotti, Alessandro
URL http://www.project-race.eu

The robot of the future will possess a great deal of general and domain-specific knowledge, it will be capable of representing in symbolic terms its perceptions, and it will most likely learn much of its knowledge from experience. In order to be competent, this robot must leverage the diverse knowledge it possesses through reasoning. Crucially, the robot's knowledge will not be expressed in one knowledge representation formalism, rather with a multitude of interdependent representations, each expressing a subset of aspects (e.g., temporal, causal, resource, taxonomic, common-sense) pertaining to the robot's capabilities, tasks and environment. This poses an important problem: although we may soon have very knowledgeable robots, all we can give them is the ability to reason within particular fragments of their knowledge. The multitude of AI reasoning algorithms that would be necessary in a realistic scenario are studied only individually, and very limited results exist in how to concurrently reason about diverse types of knowledge with current AI techniques.

This talk outlines some of the challenges in hybrid reasoning, with a particular emphasis on robot reasoning tasks. These include planning (reasoning about causal relations), temporal reasoning, symbolic and geometric spatial reasoning, scheduling (reasoning about time and resources), and ontological reasoning. The talk will outline solutions studied in the EU-FP7 RACE project. Focus will be given to a general method for hybrid reasoning grounded on the notion of meta-constraints.

4.17 Predicting Robot Action Results Physically Correct: Towards Imaginary Planning

Sebastian Rockel (Universität Hamburg, DE)

Joint work of Rockel, Sebastian; Klimentjew, Denis; Zhang, Liwei; Zhang Jianwei

Imagination enables humans to consult rules or principles but do not merely apply that rule. Instead humans imagine what the consequences might be of following or not following the rule. It is even commonly maintained that humans constantly do imaginative projection. Furthermore some works conclude that imagination is essential to human reasoning. Our approach is inspired by the concept of imagination and its goal is to employ it on a mobile robot system. The presented work uses physics-based simulation in order to predict action results. Based on robot imagination this talk shall stress supporting scenarios where simulation as the tool for common sense reasoning can be exploited. Different scenarios will be presented that demonstrate an improved performance of such an imaginary planning-based robot system compared to state-of-the-art symbolic planning approaches. A comparison between the presented techniques and a possible integration shall conclude the talk.

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4.18 Interactive Open-Ended Learning about Objects and Activities

Luis Seabra Lopes (University of Aveiro, PT)

Joint work of Seabra Lopes, Luis; Chauhan, Aneesh, Oliveira, Miguel; Kasaei, S. Hamidreza; Mokhtari, Vahid; Tomé, Ana Maria

We presented an overview of previous work on open-ended learning in robotics, with emphasis on projects in which our group is/was involved [2, 5]. Key characteristics of intelligent service robots as well as some of the issues in the development of such robots were identified [1]. The presentation then focussed on two important phases in experience-based learning, namely experience extraction and experience conceptualization. These two learning steps are addressed in two different domains, namely object category learning [4] and activity schema learning [3]. The human user, playing the role of instructor, helps to speed up and focus the learning process. Aspects of evaluation of open-ended learning were also addressed.

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4.19 Robot Tutoring

Luc Steels (Free University of Brussels, BE)

A lot of research has gone into mechanisms by which a robot could learn from experience. Usually the robot is seen as an agent that receives a corpus of data (ideally sensory states with motor states and possibly effects in the world) and performs some kind of induction to learn when certain actions are appropriate or how actions carried out by others should be interpreted. This approach certainly has to be part of the road towards learning robots. However, in the case of human learning, particularly of symbolic intelligence including language, a tutor (for example a caregiver) plays a crucial role. Learning thus becomes much more interactive. The tutor creates constrained contexts for learning, provides critical feedback, and interprets behaviors by guessing their intend and thus infuses meaning in them. For example, pointing gestures are acquired from attempts to grasp objects out of reach. The caregiver interprets failed grasping and brings the object within reach, from where the grasping gesture itself evolves to become symbolic and the basis of language games. I will argue in this talk that there is great value in studying the coupling between learning and tutoring by setting up experiments in which robots are programmed to act both as learners

and as tutors. I will show examples of this approach for different stages in the origins of symbolic intelligence grounded through sensory-motor intelligence: the discovery of symbol use, the big spurt in vocabulary, the origins of grammar, and the origins of the self.

4.20 Towards an Integrated Hierarchical Planner for Complex Robot Tasks

Sebastian Stock (Universität Osnabrück, DE)

Joint work of Stock, Sebastian; Günther, Martin; Hertzberg, Joachim

Planning and execution is crucial for the performance of complex tasks in challenging environments with a mobile service robot. Furthermore, if we want the robot to adapt its behavior based on experiences of previous execution traces, task planning can be a point to apply the learned knowledge resulting in a changed behavior. The plans can also be part of the experience itself and be used afterwards for learning. For this, hierarchical planning has the benefit of providing additional levels of abstraction to the plan generation and the resulting plans itself. To change the robot's behavior only additional methods need to be added to the planning domain or preconditions of existing methods might be changed while the implementation of operators can be fixed.

In the first two years of the RACE project an off-the-shelf HTN planner has been used. Since this imposes several limitations, ongoing work will be presented of a hierarchical planning system which is closely integrated to execution monitoring and is able to use different kinds of knowledge.

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4.21 Robot Manipulation in Human Environments: Challenges for Learning Algorithms

Carme Torras (UPC – Barcelona, ES)

Manipulator robots are widening their range of activities in factories, as well as finding increased application in human-centered domains such as healthcare, education, entertainment and services. For robots to become handy co-workers and helpful assistants, quick and user-friendly ways to endow them with flexible manipulation skills are needed. At the Perception and Manipulation Lab of IRI (CSIC-UPC), we are addressing several of the learning challenges arising in this context [1]. Namely, manipulator robots should be easy to teach by non-experts [2] and acquire skills from demonstrations [3, 4], they need to be intrinsically safe [5] able

to appropriately deal with forces [6] and to perceive and manipulate deformable objects [7, 8, 9, 10], to, tolerant to noisy perceptions and inaccurate actions [11, 12], and they must exhibit a high adaptability [13, 14] to non-predefined and dynamic environments, as well as the capability of learning to plan [15]. The cited works will be showcased along the presentation and support for their development is acknowledged from the European projects PACO-PLUS, GARNICS and IntellAct, the Spanish projects PAU and PAU+, and the Catalan grant SGR-155.

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4.22 Skill Development through Affordance-based Bootstrapping

Emre Ugur (Universität Innsbruck, AT)

Joint work of Sahin, Erol; Oztop, Erhan; Nagai, Yukie; Piater, Justus

In this talk, we introduce our robot learning framework which follows a similar timeline with human infant development. In the initial stages of the development, the robot organizes its action parameter space to form behavior primitives, and explore the environment with these primitives to learn basic object affordances such as graspability, pushability and rollability. After learning, the robot can emulate observed goals by making multi-step plans using the discovered behaviors and affordances.

The focus of this this talk will be on the next stages of development where the robot learns more complex behaviors and affordances in multi-object environments with the help of a demonstrator. Regarding to complex behavior learning, we studied how the robot can directly map demonstrated complex action trajectories to its own sensorimotor space. We proposed a mechanism that enables the robot to extract subgoals (with the help of demonstrator through motionese) and to imitate the observed complex behavior by satisfying these subgoals sequentially. The new complex behaviors that involve two or more objects should be further explored as before to learn multi-object affordances. At the end of this talk, we will discuss how multi-object affordance learning can be bootstrapped by utilizing basic affordances as additional properties of the objects.

4.23 Sensorimotor Memory: Representation, Learning and Inference

Jure Zabkar (University of Ljubljana, SI)

An efficient representation of sensorimotor system is vital to robot control and its ability to learn new skills. While the increasing sensor accuracy and the speed of signal processing failed to bridge the gap between the performance of artificial and human sensorimotor systems, the motor memory architecture seems to remain neglected. Despite the advances in robot skill learning, the latter remains limited to predefined tasks and pre-specified embodiment. We propose a new motor memory architecture that enables information sharing between different skills, on-line learning and off-line memory consolidation. We develop an

algorithm for learning and consolidation of motor memory and study the space complexity of the representation in the experiments with humanoid robot Nao. Finally, we propose the integration of motor memory with sensor data into a common sensorimotor memory.

4.24 Project Report: RACE

Jianwei Zhang (Universität Hamburg, DE)

URL http://www.project-RACE.eu

In a dynamic and changing world, a robust, adaptive and effective artificial cognitive system (ACS) must have a high-level conceptual understanding of the world it inhabits. The overall aim of RACE is to develop an artificial cognitive system, embodied by a robot, able to build such a model of the world by storing and exploiting appropriate memories of its experiences. We will demonstrate how an ACS can evolve its model as a result of novel experiences; and show how such a model allows an ACS to better understand new situations enabling it to achieve its goals in new situations at a level of robustness and effectiveness previously not achievable. Experiences is recorded as semantic spatio-temporal structures connecting high-level representations, including goals, tasks and behaviours, via their constituents at lower levels down to the sensory and actuator level. In this way, experiences provide a detailed account of how the ACS has achieved past goals or how it has failed, and what sensory events have accompanied the activities. Conceptualisations are obtained by abstracting and generalising from experiences, extending task planning and execution beyond preconceived situations. Activities successfully carried out by the ACS for specific objects at specific locations may be generalised to activity concepts applicable to classes of objects at variable locations. Conceptualisations may also result in commonsense insights, e.g. about object behaviour on tilted surfaces. The project aims at the following main results: (i) Agents capable of storing experiences in their memory in terms of multi- level representations connecting actuator and sensory experiences with high- level semantic structures,
(ii) Methods for learning and conceptualising from experiences obtained from behaviour in realistically scaled real-world environments,
(iii) Robot systems demonstrating superior robustness and effectiveness caused by experience-based planning and behaviour adaptation within incompletely specified environments.
Results will be integrated and evaluated in an operational mobile platform with grasping facilities.

4.25 Project Report: STRANDS

Michael Zillich (TU Wien, AT)

Joint work of STRANDS, Consortium; Hawes, Nick
URL http://strands-project.eu

STRANDS will produce intelligent mobile robots that are able to run for months in dynamic human environments. We will provide robots with the longevity and behavioural robustness necessary to make them truly useful assistants in a wide range of domains. Such long-lived

robots will be able to learn from a wider range of experiences than has previously been possible, creating a whole new generation of autonomous systems able to extract and exploit the structure in their worlds.

Our approach is based on understanding 3D space and how it changes over time, from milliseconds to months. We will develop novel approaches to extract spatio-temporal structure from sensor data gathered during months of autonomous operation. Extracted structure will include reoccurring 3D shapes, objects, people, and models of activity. We will also develop control mechanisms which exploit these structures to yield adaptive behaviour in highly demanding, realworld security and care scenarios.

5 Working Groups

5.1 Report Discussion Group 1

Alexandre Bernardino (Technical University – Lisboa, PT)

Joint work of All participants of the group

Scientific Questions

1. Where/How should uncertainty be dealt with in learning robots?
2. Computer Vision in Robotics (why robot vision seems somewhat disconnected from CV)?
3. How to construct a good ontology (for robot learning)?
4. What representations bridge low-level and high level?
5. Can we learn anything suitable to be used by higher levels?
6. Semantic vs low-level info
7. Can we use high-level knowledge to influence the low level?

Report. This report summarises the debate of Group 1 on the topics of theme A, listed above. The questions were not addressed by a specific order.

The starting point of the discussion was related to the utilisation of high-level knowledge in the lower levels of a cognitive architecture. In particular, the noise and percept instability in the low-level sensory sensory system were noted as major difficulties in information processing. To deal with noise some ideias were put forwards, in particular sequential (Bayes) probabilistic reasoning but maintaining logical representations from the high-level knowledge, although it is not yet clear how to go from the continuous/probabilistic information into symbols (where to put the threshold). If appropriate logical and temporal constraints are encoded, the large number of interpretations coming from the probabilistic representation cleans itself if one waits long enough. Therefore high-level models can be seen as a kind of filter that helps removing noise from the lower levels.

The next point under discussion was related to the application of computer vision in robotics. In robotics the images move constantly thus making interpretation more difficult. In some cases it is a matter of image retrieval (trying to identify known objects in the scene) but in other cases the robot itself may what to take an active role in searching for the objects. In this case ontologies, context and expectation can be helpful in the process. Anyway the problem is very complex and its seems difficult to tackle with only two levels of representation (low vs high level) because of big differences between them. More intermediate representations, with less variation among consecutive ones would probably simplify the

planning levels. In particular some semantic levels could go lower in the hierarchy, even if names cannot be assigned to the managed symbols. Assigning names to symbols or having 1-to-1 mappings between words and symbols was considered not essential. Anything that can be labeled may carry semantic meaning.

Discussion then concentrated on how to build a good ontology. It was made a distinction between the purpose of the ontology: learning vs planning. Different purposes may demand ontologies with different characteristics. For learning it is important to have compositionally but no recursion. For planning it is important to have recursion. Then, appropriate translations are needed to convert among them. Good ontologies are also important for knowledge sharing (provide an organised way to share information), and for efficient reasoning. Another difficulty is related to different meanings of items in an ontology (example of the match box, candle and pin – the matchbox can be used as a support for the candle, which is not is common usage). For these cases we may need multiple ontologies and ways to switch between them. Also it is important to have languages supporting generalisation of concepts like ILP.

In the last point, it was discussed if ontologies are really needed or if we can just use all the stored experiments. One problem of using data alone is the need to define similarities between examples which is hard in high-dimensional spaces. In fact, is a similarity metric can be defined, it can also implicitly define an ontology, but needs to adjust to different situations and is not trivial. An example is obstacle avoidance. There is no concept of an obstacle (e.g. a chair) but just examples of failures to move associated to examples of chairs. Upon the observation of another chair, how to generalize ? By learning, we build a taxonomical representation "anything with bounding box of this shape is an obstacle". But again similarity is hard to assess, as largely debated in the book: The Subtlety of Sameness: A Theory and Computer Model of Analogy-making, by Robert Mills French.

5.2 Report Discussion Group 2

Alexandre Bernardino (Technical University – Lisboa, PT)

Joint work of All participants of the group

Scientific Questions

1. Domain adaption, knowledge transfer
2. Cross-modal learning
3. Learning strategies. Weakly supervised learning
4. What is the role of affordances (in robot learning, control and planning)?
5. One shot learning vs statistical learning
6. Learning over long (life) periods of time

Report. The discussion group addressed the questions in order. Below are listed the main points discussed for each one question.

1. The problem of domain adaption and knowledge transfer can be tackled by realising what is the transformation between the domains that may lead to the adaption of the behaviours. It can be as simple as estimating a parameter that maps the domains (e.g. calibration) or very hard in complex domains. Even in the simple one parameter case it may be hard to generalize. For example, consider shooting a ball of different weights.

If we use a football, the most efficient way is to kick it fast with the foot. However, if you try to generalize to a bowling ball, you need a very different strategy: hold with the hand, swing to gain momentum and then throw. There is continuous transition in the weight of the ball but a very significantly difference in the extreme cases.

2. Cross-modal learning is related to learning from different sensor modalities and creating associations between them. Having several sensor modalities is important to have a more complete perception of the environment – individual sensors may not be enough to sort out the relevant information in the environment. However, it brings many challenges like synchronisation between modalities, temporal segmentation, extraction of the right features, etc. The diversity of way to associate data between the different modalities may lead to high computational complexity.
3. Regarding learning strategies, the group debated whether it is beneficial to start learning in a simplified domain (easy to discover some basic principles) and then use them when learning in full sized domain (although some laws will have to be modified, refined to special cases). Example: learn about moving balls (snooker balls) in a limited plane with obstacles around. One could think of a staged learning approach: (i) start with a ball in infinite domain; (ii) then increase the number of balls; (iii) then include obstacles and limits on the plane. The approach seems reasonable but there are cases where things may work better otherwise. For example in chess teaching, adults start learning the movements of individual pieces, but for children it is better to teach the hole game from the start. Still in this point it was debated weakly supervised learning. In principle this method is able reduce the labelling effort but may be more sensitive to (weak)- label mistakes. Training data is critical.
4. Affordances are a complex concept with many alternative interpretations. One of the interpretations can be related to the pre-conditions for the application of actions on objects (object shape, position, orientation, etc). Under this interpretation it is possible to assess the key role of affordances in robot-learning, planning and control.
5. One shot learning vs statistical learning. It was discussed that one-shot learning may be enough with enough prior knowledge and/or simple domains. For instance, children can learn to recognise giraffes from a single picture. However, a giraffe is a very distinctive animal with respect to the other. In cases where the distinction between classes is more ambiguous, statistical learning and many more examples may be required.
6. The problem of learning over long life periods of time was the last point of discussion on this session. The most critical aspect of this type of learning was related to knowledge management. Learning over long period of time require to compress the examples acquired (it is impossible to keep all the examples in memory), so issues like forgetting and remembering and of great relevance and not very much explored in the literature. Other aspect related to continual learning it how to explore the world to learn fast. This is sometimes denoted as active learning. With adequate exploration strategies, a robot can learn more efficiently. Finally, having huge amounts of data may lead to overfitting (learning too specific examples and do not generalize well). To prevent this effect, classical machine learning methodologies can be used, e.g. cross-validation.

5.3 Report Discussion Group 4a

Laurent Orseau (AgroParisTech – Paris, FR)

Joint work of Bernd Neumann; Laurent Orseau; Georgi Stojanov; Markus Vincze

Participants of the group: Bernd Neumann, Laurent Orseau, Georgi Stojanov, Markus Vincze.

1. The question was whether we should adopt a systemic perspective of all the topics discussed during the seminar, i.e. whether we should keep in mind the global picture and the long term goals of robotics. We (the group of 4 participants) unanimously agreed that it was preferable.
2. The underlying question is: "What is the level of autonomy that we want for a robot?". Should robots be able to modify themselves entirely? The example of the Gödel Machine [1] was taken as an example of such an agent. Self-modification is related to learning since learning modifies the parameters of the underlying system. For moderately intelligent robots such as service robots, it does not seem that full self-modification is useful. However, it must be noted that (human-level) intelligent robots will nonetheless be able to modify themselves entirely, possibly by indirect means like asking someone else.
3. The framework presented in [2] makes a clear distinction between the source code and the memory of the agent: Knowledge and reasoning are separated into two entities. Although it is a practical separation for the cited work, it is not clear that it is a necessary or even a useful assumption for robotics.y It must be noted that the human brain actually takes the completely opposite approach: memory and processes are completely entangled.
4. Common sense has been a desirable feature since the beginnings of robotics, but has never been properly tackled. Everyone is focusing on more short-term tasks. According to some in the discussion group, ontologies are probably not going to solve this problem, as it seems unlikely that we can handcraft all common sense knowledge in advance. So we probably need something different.
   Learning the (intuition of the) laws of physics can be important to predict the effects of actions like pulling a notepad on which there is a pen. Will the pen roll and fall, or will it come with the notepad? Humans seem to reason by predicting the consequences of actions, but the kind of reasoning seem to be context-dependent (e.g., depending on what to focus on), and so it is not clear that common-sense is always about prediction.
   Learning common sense seems to be a big challenge. The group suggested the possibility to build a robot that, in a first phase, is meant to learn without a particular goal, so as to accumulate common-sense, much like Pierre-Yves Oudeyer's curiosity learning robots [4], or Laurent Orseau's knowledge-seeking agents [3], the latter of which chooses its actions so as to maximise the entropy of the possible outcomes, in order to gain as much information about the world as possible. In the second phase, copies of the robot could be specialised for various tasks suitable for a service robot.
5. Designing rewards can be very complicated, in particular if we want autonomous agents. The example of a gliding agent in a maze was taken: If we want the agent to move around the maze, it is not sufficient to merely give a reward to the agent for moving forward and punishment for hitting walls, as the agent may then simply turn in circles, which indeed maximises the expected reward. This shows that designing a reward function is far from trivial. In particular, for a service robot that can be rewarded and punished through a

remote-control, it should require only moderate intelligence and common sense for the robot to realise that it should acquire the remote-control to press the reward button itself. The question of designing a good reward function becomes quite complicated when we consider multidimensional rewards, in particular when considering the interactions between various rewards. It was also discussed whether rewards should be defined once and for all or if rewards could change in time, seemingly by analogy with how humans change their preferences. However, it was not clear whether it is the rewards or the values that change.

5.4 Report Discussion Group 4b

Sebastian Rockel (Universität Hamburg, DE)

Joint work of Rockel, Sebastian; Stock, Sebastian; Konecny, Stefan; Saffiotti, Alessandro; Lehmann, Jos; Hotz, Lothar; Bratko, Ivan; Möller, Ralf; Cohn, Anthony

Participants of the group: Ivan Bratko, Anthony Cohn, Alessandro Saffiotti, Ralf Möller, Lothar Hotz, Jos Lehmann, Sebastian Rockel, Sebastian Stock, Stefan Konecny.

Scientific Questions

1. Should we take a system perspective on the above questions?
2. Theoretical framework for learning agents
3. Self-modifying agents, representations vs. processes
4. Learning common sense, meta-knowledge

Report. 1 and 4 – Learning common sense and learning meta-knowledge should be viewed at separately as they are different types of knowledge. Although meta-knowledge does include some common sense knowledge. Examples for common sense would be how to use tools (and if at all). For learning common sense knowledge it is required being able to represent qualitatively physics.

There are different representations of common sense knowledge: e.g. learning from infants vs. learning with formulas. It is also important to state that humans share common sense with animals. An example for meta-knowledge on the contrary would be: "Knowing that I don't know". Furthermore the discussion group points out that uncertainty has a notable relation to meta-knowledge.

A valid robotics related question is: "How should robots be built up with an understanding capability of common sense knowledge?" Common sense knowledge as a separate form of knowledge (besides spatial, temporal etc.). Learning common sense knowledge once and transfer it to multiple (different) robots is a desirable goal when it comes to sharing knowledge between robots. Learning common sense is lacking negative examples. Thus dedicated learning methods, such as clustering, have to be applied.

A wide consensus within the group is the openness of a definition for "common sense". A direct question to this is: "If at all to learn common sense or rather define it once (and use it again)?" An agreed definition proposal within the group is (common sense): Everything learned (by a child) out of pure curiosity is considered to be common sense knowledge. Furthermore Common sense is more than naive physics reasoning, e.g. following statement is also considered to be common sense: "You get a cold outside when not dressed appropriately in winter."

Present knowledge representation and learning systems are not well suited when faced with common sense reasoning, e.g. using ontologies. Common sense in AI is not explored well as of today. Learning it is certainly a desired capability of a robot, but not much has been done yet in this field yet. Although it is an attractive way to acquire it by learning. In principle human common sense can be shared with robots.

In summary, common sense is useful for robots, especially in domestic environments. It is not usable as of today (in general) with present tools, only in constrained scenarios with a constrained knowledge base.

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Report from Dagstuhl Seminar 14082

Visualization and Processing of Higher Order Descriptors for Multi-Valued Data

Edited by

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Abstract

This report documents the program and the outcomes of Dagstuhl Seminar 14082 "Visualization and Processing of Higher Order Descriptors for Multi-Valued Data". The seminar gathered 26 senior and younger researchers from various countries in the unique atmosphere offered by Schloss Dagstuhl. The focus of the seminar was to discuss modern and emerging methods for analysis and visualization of tensor and higher order descriptors from medical imaging and engineering applications. Abstracts of the talks are collected in this report.

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1 Executive Summary

Ingrid Hotz
Anna Vilanova Bartroli

Higher Order Descriptors for Multi-Valued Data

This seminar is the 5th in a series of Dagstuhl Seminars devoted to the visualization and processing of higher-order descriptors, of which tensors are a special case. They provide a natural language to describe phenomena in physics or image processing, e.g. medical imaging, fluid dynamics, or structural mechanics. Due to the increasing complexity of data generated in the engineering industry and the rapid advances in medical imaging, multi-valued data have gained significant importance in scientific visualization and image processing. Compared to their importance analysis and processing tools are still relatively rare.

In many scientific and engineering applications, as modern product development processes, simulations are an essential part of the advancement of the field. The results are large and complex data sets often comprising multi-filed data of various kind. Thereby, the tensor concept is essential for the description of physical phenomena related to anisotropic behavior.

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Examples for second-order tensors are stress and strain fields, inertia tensors, and orientation distribution tensors. Higher-order tensors occur when multiple vector fields or second-order tensors are set into relation, e.g., the stiffness tensor relating stress and strain. The field of engineering faces many open problems in tensor field analysis and visualization.

In medical imaging, multi-valued data include diffusion-weighted magnetic resonance imaging (dMRI), a medical imaging modality that allows the measurement of water diffusion in tissue (e.g., white matter or muscle) in vivo. Simple models approximate the diffusion in fibrous tissue by a second-order diffusion tensor (i.e., a positive semi-definite 3×3 matrix). But, often the acquired data is more complex and cannot be sufficiently described by the second-order tensor model and requires higher-order descriptors (i.e., higher-order tensors or spherical harmonics).

Even though these applications are very different in their nature they face many shared challenges associated with this highly complex data, which can profit from a multidisciplinary approach. The idea of this Dagstuhl Seminar was to bring together key researchers for disciplines ranging from visualization and image processing to applications in structural mechanics, fluid dynamics, and numerical mathematics.

Seminar Topics and Breakout Sessions

The seminar has been organized in presentation and breakout sessions. The presentation sessions gave the participants the possibility to presented recent developments in the multidisciplinary field. The talks covered a broad variety of topics related to both theoretical and practical issues. They served as basis for inspiring discussions across the application areas, which demonstrated that there are many shared issues related to analyzing and visualizing fields of tensors and higher-order descriptors. Besides the presentations, we put an emphasis on breakout sessions, which were very successful already in the previous meeting. They were targeted at fostering focused discussions in smaller groups. During a first session the group defined some driving objectives that partially already emerged in preparatory discussions:

- Statistics on higher-order descriptors and visualization of uncertainty
- Generalization of mathematical framework to higher-order descriptors
- Features on tensor visualization
- Next generation diffusion MRI

Most issues identified in the call have been discussed. Subjects that found special attention can be summarized as: Fundamental general topics, as tensor interpolation, statistics, morphology, and topology; Questions related to pattern description and detection; More specific issues like the analysis of ensembles, the visualization and measurement of differences and anomalies for engineering as well as for medical data sets. Further, there has been much interest in double pulse field gradient methods that have been discussed as possible next generation diffusion MRI. The outcome of the sessions can also be seen at http://www.dagstuhl.de/wiki/index.php/14082#Breakout_topics

The breakout sessions again turned out to be very successful. The format of the breakout sessions fits very well in the Dagstuhl environment promoting discussions and interactions. We could also observe that, for some topics, it is not easy to go beyond a list of challenges in such a short time frame. This motivates to strengthen these sessions by pre-defining topics in preparation of the meeting and asking selected participants for related statements.

Outcomes

The participants all agreed that the meeting was successful and stimulating. Seminar participants are already collaborating on a Springer book summarizing the results of the meeting. The Springer book will have about seventeen chapters authored by the meeting participants. It is also planned to summarize the results of two breakout sessions as a chapter of the book. The participants Thomas Schultz and Ingrid Hotz agreed on taking the lead for the collection of the contributions and the assembly of the book. We expect the book to be published in 2015.

It was voted that the group will apply for another meeting in this series, and that in addition to the current organizer (Ingrid Hotz) there will be two new organizers (Thomas Schultz, University Bonn Germany and Evren Özarslan, Harvard Medical School – Boston, US) for the next event.

Acknowledgement

The organizers thank all the attendees for their contributions and extend special thanks to the team of Schloss Dagstuhl for helping to make this seminar a success. As always, we enjoyed the warm atmosphere of the Schloss, which supports both formal presentations as well as informal exchanges of ideas.

2 Table of Contents

3 Overview of Talks

3.1 Morphology for Color Images by Means of Loewner Order and Einstein-Addition for Matrix Fields

Bernhard Burgeth (Universität des Saarlandes, DE)

Joint work of Burgeth, Bernhard; Kleefeld, Andreas

In this talk we present an approach to (elementary) morphology for colour images that relies on the existing order based morphology for matrix fields of symmetric 2×2-matrices. An RGB-image is embedded into a field of those 2×2-matrices by exploiting the geometrical properties of the order cone associated with the Loewner order. To this end a modification of the HSL-colour model and a relativistic addition of matrices is introduced. Some experiments performed with elementary morphological operators on synthetic and natural images give an idea of the capabilities and limitations of the novel approach.

3.2 Control and Edit Higher-Order Tensor Fields for Hex-Meshing

Guoning Chen (University of Houston, US)

Hexahedral meshes have been widely applied in the areas of mechanical engineering, biomechanics, and many others. Compared to the easily generated tetrahedral meshes, hex-meshes offer a number of desired characteristics. For example, they are 1) locally structured and thus favor the exploiting of tensor product structure; 2) easy to refine, facilitating the implementation of multi-grid and adaptive computations; 3) having larger tolerance for anisotropy and less numerical stiffness. These characteristics facilitate subsequent scientific computations that are run on these meshes, such as certain physically-based simulations, so that the generated results are of higher accuracy and faster to compute.

Recently introduced techniques rely on either PolyCube map or a 3D cross field, a 4th-order symmetric tensor field, to compute a 3D parameterization of the volume for the generation of the hex-meshes. PolyCube map approach focuses on the structure of the parameterization near surfaces and can be considered, in some sense, a special case of the cross field approach, which provides information of the interior structure of the 3D parameterization as well. However, the structure of the generated hex-meshes, determined by the irregular edges and vertices, with either method is hard to predict and control.

We recently introduced a method to combine the advantages of the Polycube approach and the cross field method to achieve certain level of explicit control of the hex-mesh structure. The structure of the hex-meshes generated by our method is typically very simple, i.e. having fewer hexahedral elements or larger tensor product structure. This facilitates the subsequent data fitting process. However, the generated hex-meshes exhibit large local distortion in certain areas due to the enforcement of simplicity of the structure. We are currently investigating the possible operations that allow us to refine this simple structure by introducing more smaller hexahedral components to reduce the local distortion. On the other hand, we are interested in simplifying the structure of the hex-meshes generated by

other methods. Either problem requires the understanding of the valid topological operations of a higher-order tensor field, to which the structure of the hex-mesh can be mapped, so that all-hex configuration of the mesh is preserved and no T-junctions are introduced during the modification. What are those possible valid operations? I would like to discuss this in the seminar.

3.3 Geometrical Diffusion Imaging

Tom Dela Haije (TU Eindhoven, NL)

Joint work of Dela Haije, Tom; Fuster, Andrea; Florack, Luc

By analyzing the behavior of stochastic processes on a Riemannian manifold, in particular Brownian motion, one can deduce the metric structure of the space. This fact was implicitly used by O'Donnell et al. in a 2002 paper, in which diffusion tensor imaging data of the brain was cast into a Riemannian framework. By presuming the existence of an inner product, intuitively defined by the inverse of the diffusion tensor, they could for example visualize the apparent connectivity between different brain regions. Conversely it is possible to derive the stipulated relation between the diffusion tensor and the Riemannian metric tensor from this inner product presumption alone.

In this work we present an attempt to generalize the Riemannian diffusion MRI framework to a Finsler geometry setting, relying only on the existence of a more general norm than the one induced by an inner product. We investigate if and how this allows the diffusion weighted MRI signal to be related to the Finslerian metric structure.

3.4 Visual Embedding: A Model for Visualization

Çağatay Demiralp (Stanford University, US)

Joint work of Demiralp, Çağatay; Heer, Jeffrey
Main reference http://www.cs.stanford.edu/~cagatay/vismodel/vismodel.pdf

In my talk, I'll propose visual embedding as a model for automatically generating and evaluating visualizations. A visual embedding is a function from data points to a space of visual primitives that measurably preserves structures in the data (domain) within the mapped perceptual space (range). I'll demonstrate with examples that visual embedding can serve as both a generative and an evaluative model. I'll briefly discuss techniques for generating visual embedding functions, including probabilistic graphical models for embedding within discrete visual spaces. I'll also describe two complementary approaches–crowdsourcing and visual product spaces–for building visual spaces with associated perceptual distance measures (perceptual kernels). I'll finish my talk by presenting future research directions for further developing the visual embedding model.

3.5 DTI Interpolation in 5 Dimensions

Luc Florack (TU Eindhoven, NL)

Joint work of Florack, Luc; Dela Haije, Tom; Fuster, Andrea
Main reference L. M. J. Florack, A. Fuster, "Riemann-Finsler Geometry for Diffusion Weighted Magnetic Resonance Imaging", in C.-F. Westin, A. Vilanova, B. Burgeth, eds., "Visualization and Processing of Tensors and Higher Order Descriptors for Multi-Valued Data", Springer-Verlag, 2014, to appear.

Diffusion Tensor Imaging (DTI) is a well-known model for the representation of diffusion weighted magnetic resonance images. It is popular by virtue of its simplicity and the fact that it strikes a good balance between signal fit and robustness. However, problematic issues remain. One of these concerns the problem of subvoxel spatial interpolation, especially in highly inhomogeneous regions. As an example, consider two similar white matter fiber bundles in a planar sheet, crossing at right angles. Off-center the (level sets of the) apparent diffusion coefficients (ADCs), which in the DTI model are quadratic forms in the q-space variable, are prolate spheroids that capture the directions of the individual bundles well. However, because the DTI assumption forces ADCs to fit quadratic forms, destructive interference of diffusivity patterns within the crossing region results in oblate spheroids, completely erasing any information on the interfering directionalities. This phenomenon also affects interpolation of DTI data. For certain applications, notably tractography, one would like an interpolated DTI tensor to reflect not only some weighted average of its given grid neighbours, but also to support a priori knowledge about the direction of tracking. For instance, when considering interpolation in the aforementioned example it would make sense to stress the prolate spheroids along one of the two bundles if one happens to be tracking in the direction of that bundle, resulting in an appropriate prolate spheroidal interpolation profile rather than an indeterminate figure. It turns out possible to do this from a single interpolation (not requiring the specification of an a priori preferred direction) involving all grid points in the volumetric neighbourhood of the subvoxel location of interest. However, the interpolated ADC function ceases to be a quadratic form, but constitutes a (much richer) homogeneous function of degree 2 with respect to the q-space variable. The indicatrix (a fiducial level set of this function) is still convex, but no longer ellipsoidal. Any choice of a preferred direction singles out an ellipsoidal, so-called "osculating indicatrix", corresponding to a quadratic form. In other words, one may regard the interpolated ADC as a family of DTI tensors, parametrized by orientation. Orientation thus adds two dimensions to the three dimensional spatial domain, forming a so-called projective sphere bundle.

3.6 Geodesic Interpolation of Fourth-order Tensors

Andrea Fuster (TU Eindhoven, NL)

Joint work of Fuster, Andrea; Schultz, Thomas

Tensor interpolation is valuable for any application requiring computation of tensor values at subvoxel level or in between data points. One of the alternatives to component-wise linear interpolation is the so-called geodesic interpolation proposed by Pennec et al. In this framework, second-order tensors are considered to live in a certain Riemannian manifold, and the geodesic connecting two tensors is used to find the interpolated tensor. We propose

to apply this framework to the interpolation of fourth-order tensors, by considering the corresponding six-dimensional matrization. In doing so, we distinguish two cases: fourth-order tensors satisfying major and minor symmetries, e.g. elasticity tensors, and those being totally symmetric such as higher-order diffusion tensors.

3.7 Comparative Visual Analysis of Lagrangian Transport Measures in Ensembles

Christoph Garth (TU Kaiserslautern, DE)

Joint work of Garth, Christoph; Hummel, Mathias; Obermaier, Harald
Main reference M. Hummel, H. Obermaier, C. Garth, K. I. Joy, "Comparative Visual Analysis of Lagrangian Transport in CFD Ensembles," IEEE Trans. Vis. Comput. Graph., 19(12):2743–2752, 2013.
URL http://dx.doi.org/10.1109/TVCG.2013.141

Sets of simulation runs based on parameter and model variation, so-called ensembles, are increasingly used to model physical behaviors whose parameter space is too large or complex to be explored automatically. Visualization plays a key role in conveying important properties in ensembles, such as the degree to which members of the ensemble agree or disagree in their output. For ensembles of time-varying vector fields, there are numerous challenges for providing an expressive comparative visualization, among which is the requirement to relate the effect of individual flow divergence to joint transport characteristics of the ensemble. Yet, techniques developed for scalar ensembles are of little use in this context, as the notion of transport induced by a vector field cannot be modeled using such tools. We report on recent work towards developing a framework for the comparison of flow fields in an ensemble, and speculate on applications of our framework to tensor fields.

3.8 Moment Invariants for Pattern Recognition

Hans Hagen (TU Kaiserslautern, DE) and Max Langbein (TU Kaiserslautern, DE)

Joint work of Hagen, Hans; Langbein, Max

Higher-order moment tensors are a very generic description of the local behavior in point-clouds, scalar, vector, and tensor fields. Having a method at hand to compute the values of a complete and independent set of invariants from then from them in a efficient and robust manner, this can be used to recognize objects and features in fields and in surfaces described by point-clouds. In this talk, the computation of a specific type of invariants and their use to recognize features in point-clouds will be described.

3.9 Heat Kernel Signature for Tensor Fields

Ingrid Hotz (German Aerospace Center – Braunschweig, DE)

Joint work of Hotz, Ingrid; Zobel, Valentin; Reininghaus, Jan

We propose a method for visualizing two-dimensional symmetric tensor fields using the Heat Kernel Signature (HKS). The HKS is derived from the heat kernel and was originally introduced as an isometry invariant shape signature. The time parameter of the heat kernel allows a multi-scale analysis in a natural way. By considering a positive definite tensor field as a Riemannian metric the definition of the HKS can be applied directly. To investigate how this measure can be used to visualize more general tensor fields we apply mappings to obtain positive definite tensor fields. The resulting scalar quantity is used for the visualization of tensor fields. For short times it is closely related to Gaussian curvature, i.e. it is quite different to usual tensor invariants like the trace or the determinant.

3.10 Learning Optimal Q-space Sampling Metrics

Hans Knutsson (Linköping University Hospital, SE)

We present a novel approach to determine a local q-space metric that is optimal from an information theoretic perspective with respect to the expected signal statistics. The signal statistic is obtained from the expected distribution of the diffusion propagators present. The obtained metric can then serve as a guide for the generation of specific q-space sample distributions. It should be noted that the approach differs significantly from the classical estimation theory approach, e.g. one based on Cramer-Rao bounds. The latter requires a pre-defined mathematical representation, the estimator. Our suggestion aims at obtaining the maximum amount of information without enforcing a particular feature representation.

To obtain the statistics of the q-space signals we generate a large number of q-space response examples. Using these examples correlation estimates between any two q-space locations, as well as correlations between different instances of the same location, can be estimated. From these correlations the added information from measuring in a second q-space location, given a first measurement in any other location, can be found.

3.11 Engineering Tensor Visualization: To ML or not ML?

Georgeta Elisabeta Marai (University of Pittsburgh, US)

Joint work of Marai, Georgeta Elisabeta; Givi, Peyman; Yilmaz, Levent; Mehdi, Nik; Maries, Adrian

Computational tensor fields are very large and spatially dense. We attempt to identify effective visual descriptors for volume rendering the combustion tensor data. Does Machine Learning (ML) for Visualization capture features of interest in such data sets? We evaluate several visual descriptors, including the result of a machine learning classification technique, on several computational-combustion data sets and report on our findings.

3.12 Finding Ring-like Patterns in Local Orientation Distributions

Rodrigo Moreno (Linköping University Hospital, SE)

Vesselness filters aim at enhancing tubular structures in medical images. The most popular vesselness filters are based on Eigen analyses of the Hessian matrix. However, Hessian-based methods have well-known limitations, most of them related to the use of second-order derivatives. In this talk, I propose an alternative strategy in which ring-like patterns are sought in local orientation distribution of gradients. The method takes advantage of the symmetry properties that these ring-like patterns show in the spherical harmonics domain. From such an analysis, a vesselness measurement is proposed.

In order to discourage the enhancement of dark vessels, gradients not pointing towards the center are filtered out from every local neighborhood in a first step. Afterwards, an orientation distribution is generated from the remaining gradients which are weighted with a Gaussian filter. Next, the power spectrum in spherical harmonics is computed for both the original and a half-zeroed orientation distribution. From both power spectra, the even, odd and DC components are extracted. Finally, the even and DC ratios of both distributions plus the strength of the original distribution are combined into a single vesselness measurement. Preliminary results show that the proposed filter performs better compared to traditional approaches in both synthetic and computed tomography angiography data.

3.13 White Matter Asymmetry Methods using Diffusion MRI

Lauren O'Donnell (Harvard Medical School – Boston, US)

Brain asymmetries provide mysterious clues about the brain's functional organization. For example, known left-greater-than-right asymmetries relate to the localization of language function to the left hemisphere in most right-handed subjects. But interestingly, increased symmetry of the arcuate fasciculus (language-related) fiber tract correlates with improved verbal recall performance. Much remains to be learned about how morphological symmetries may underlie major functional differences across the hemispheres.

The development of new methods to measure white matter (WM) asymmetry using diffusion tensor MRI (DTI) may provide biomarkers for presurgical localization of language function and improve our understanding of neural structure-function relationships in health and disease. The question of how best to measure WM asymmetry is open. We will review existing methods for the study of WM asymmetry and present results from a hypothesis-free method for measurement of asymmetry in the entire WM.

3.14 Mean Apparent Propagator (MAP) MRI: A Novel Representation of Three-Dimensional Diffusion MRI Data

Evren Özarslan (Bogaziçi University – Istanbul, TR)

Joint work of Özarslan, Evren; Koay, Cheng Guan; Shepherd, Timothy M.; Komlosh, Michal E.; Irfanoglu, M. Okan; Pierpaoli, Carlo; Basser, Peter J.
Main reference E. Özarslan, C. G. Koay, T. M. Shepherd, M. E. Komlosh, M. Okan Irfanoğlu, C. Pierpaoli, P. J. Basser, "Mean Apparent Propagator (MAP) MRI: a novel diffusion imaging method for mapping tissue microstructure," Neuroimage, 78:16–32, September 2013.
URL http://dx.doi.org/10.1016/j.neuroimage.2013.04.016

Diffusion-weighted Magnetic Resonance (MR) signals can be transformed into profiles of diffusive displacements, which contain information about underlying tissue microstructure and cytoarchitecture. We previously proposed [1] an efficient representation of the MR signal decay via Hermite functions leading to accurate estimates in the high- as well as low-frequency regimes of the displacement profiles. MAP-MRI [2] is a new framework that combines three such representations with possibly different scale parameters assigned to each of the three principal orientations of diffusion. The lowest order term on the resulting series contains a diffusion tensor that characterizes the Gaussian displacement distribution, equivalent to that assumed by diffusion tensor MRI (DTI), while inclusion of higher order terms enables the reconstruction of the true apparent propagator. Since the propagator is represented as a vector in an abstract space, it is meaningful to measure the (dis)similarity of two propagators via an angular metric. Such a measure was used to introduce several scalar indices leading to interesting contrasts in the brain. MAP-MRI's overall mathematical structure resembles tensorial representations albeit with different transformation properties.

References

1 Özarslan, E., Koay, C. G., Basser, P. J., 2008. Simple harmonic oscillator based estimation and reconstruction for one-dimensional q-space MR. In: Proc Intl Soc Mag Reson Med. Vol. 16. p. 35.
2 Özarslan, E., Koay, C. G., Shepherd, T. M., Komlosh, M. E., İrfanoğlu, M. O., Pierpaoli, C., Basser, P. J., 2013. Mean apparent propagator (MAP) MRI: a novel diffusion imaging method for mapping tissue microstructure. NeuroImage 78, 16–32.

3.15 Multiscale Feature Preserving Volume Visualization

Renato Pajarola (Universität Zürich, CH)

Joint work of Pajarola, Renato; Suter, Susanne K.
Main reference S. K. Suter, M. Makhinya, R. Pajarola, "TAMRESH: Tensor approximation multiresolution hierarchy for interactive volume visualization," Computer Graphics Forum, 32(3pt2):151–160, 2013.
URL http://dx.doi.org/10.1111/cgf.12102

In this talk we will review a novel and recently proposed method for higher-order decomposition of large scale multi-dimensional visual data into multi-linear bases and corresponding coefficients, suitable for interactive visualization applications. This tensor-approximation based volume representation features compact data storage, it supports efficient spatially selective random access at variable resolution, and it allows for multi-scale feature preserving reconstruction; all critical and desired properties in an interactive scientific visualization

environment. We will also focus on and discuss the multi-scale feature expressiveness of such data decomposition and reconstruction approaches, as well as on further data processing that can be supported efficiently in the decomposition domain.

3.16 Diffusion Tensors from Double-PFG MRI Experiments

Ofer Pasternak (Harvard Medical School – Boston, US)

Double-pulsed field gradient (double PFG) is a generalization of the single PFG acquisition methods that is conventionally used in diffusion MRI. Instead of applying a single pair of sensitizing gradients, the double PFG acquisition applies two pairs of sensitizing gradients (separated by a mixing time), and as a result the attenuation is affected by the combined effect of molecule displacement during the two pairs. The approach was recently implemented on clinical scanners, allowing in-vivo human scans. Different applications have demonstrated that varying the angle between the two pairs result with signal modulation that provides information about anisotropies that cannot be measured with single PFG. Double PFG was also utilized to measure exchange between compartments. In this context of exchange measurement, it is common to refer to the first gradient block as a filtering block, which is designed to attenuate fast diffusing water molecules, such as those found in the extracellular space. Here, we propose to use the terminology of filtering blocks, combined with a specialized gradient acquisition scheme in order to provide a simple model, which relates a special case of the double PFG signal to diffusion tensors. By using a tensor model we are able to make an intuitive connection between the single and double PFG methods, which also allows application of existing DTI analysis methods and tools.

3.17 Frames for Tensor Field Morphology

Jos B. T. M. Roerdink (University of Groningen, NL)

Joint work of Van de Gronde, Jasper J.; Roerdink, Jos B.T.M.
Main reference J. J. van de Gronde, Jos B. T. M. Roerdink, "Frames for Tensor Field Morphology," in Proc. of the 1st Int'l Conf. on Geometric Science of Information (GSI'13), LNCS, Vol. 8085, pp. 527–534, Springer, 2013; the author provides a webpage with related sourcecode.
URL http://dx.doi.org/10.1007/978-3-642-40020-9_58
URL http://bit.ly/15MoLEI

Initiated in the 1960s, mathematical morphology was developed to describe image operators for enhancement, segmentation, and extraction of shape information from digital images. In contrast to traditional linear image processing, the morphological image operators focus on the geometrical content of images and are nonlinear. Their mathematical description has been extensively developed within the framework of partial orders and complete lattice theory, and many efficient algorithms are available for binary and grey scale images. Also, the case of vector-valued data, such as color or hyper-spectral images, has been addressed. Our current work focuses on the development of (hyper-) connected, adaptive and multi-scale morphological filters for matrix- and tensor-valued images. A major hurdle is the fact that there is no obvious partial order on tensors.

From the theoretical point of view, an important aspect in the design of morphological operators is their invariance under translation, rotation or scale changes, or, more generally, under an arbitrary group of transformations. A recent approach to group invariance (and particularly rotation invariance) for tensor fields is presented, based on the concept of frames. Open problems will be discussed.

References

1 Jasper J. van de Gronde and Jos B. T. M. Roerdink. *Group-Invariant Frames for Colour Morphology*. Proc. 11th International Symposium on Mathematical Morphology (ISMM 2013), May 27-29, Uppsala, Sweden, C. L. Luengo Hendriks, G. Borgefors and R. Strand (eds.), LNCS 7883, 267–278, 2013.

2 Jasper J. van de Gronde and Jos B. T. M. Roerdink. *Frames for Tensor Field Morphology*. Proc. Geometric Science of Information, F. Nielsen and F. Barbaresco (eds.), LNCS 8085, 527–534, 2013.

3 Jasper J. van de Gronde and Jos B. T. M. Roerdink. *Group-Invariant Colour Morphology Based on Frames*. IEEE Transactions on Image Processing, 23 (3), 1276–1288, 2014.

3.18 Tensor Lines in Engineering – Success and Open Questions

Gerik Scheuermann (Universität Leipzig, DE)

Joint work of Scheuermann, Gerik; Zobel, Valentin; Stommel, Markus; Schöneich, Marc; Burgeth, Bernhard; Kratz, Andrea; Hotz, Ingrid

After the previous Dagstuhl meeting on Tensor Processing and Visualization, a team of mathematicians, visualization researchers, and engineers started an intense cooperation. This became a real success story: Tensor lines can sometimes lead to substantially better component designs, especially for rib design. However, in other cases, we were not able to repeat this success. In the talk, we review the success and failure cases and suggest directions of further research.

3.19 Tensor Visualization – A Tool for Engineers in the Virtual Product Development Process

Marc Schöneich, Markus Stommel (Universität des Saarlandes, DE)

Joint work of Kratz, Andrea; Schöneich, Marc; Zobel, Valentin; Burgeth, Bernhard; Scheuermann, Gerik; Hotz, Ingrid; Stommel, Markus
Main reference A. Kratz, M. Schöneich, V. Zobel, B. Burgeth, "Tensor Visualization Driven Mechanical Component Design," in Proc. of the 2014 IEEE Pacific Visualization Symp. (PacificVis'14), pp. 145–152, IEEE, 2014.
URL http://dx.doi.org/10.1109/PacificVis.2014.51

This contribution starts with a short introduction to nowadays development process of technical parts. Important computer aided tools are described which are used by the engineer in the context of virtual product development. Based on typical time schedules of product development processes the need for efficient visualization tools for the engineer is derived. This not only aimed at producing powerful pictures by visualization techniques but also in

filtering the multidimensional data towards significant information and using as much as possible of the information in i.e. tensorial technical information.

The significance of tensor visualization in designing technical parts is presented in the second part as a major result of a close collaboration between mechanical engineers and visualization researchers to base the part topology optimization on visualisation techniques using specific tensorial information. The investigated tensor lines (lines tangential to the principal stresses) are related to the major load paths from the operating loads to the fixation points of a technical part. Hence, tensor lines can be considered as a central component in the structure design process. The guidance of the design of rip structures in injection moulded plastic parts by selected tensor lines will result in an optimized rip structure which leads to stiffer parts with identical material use. FE simulations as well as experimental tests validate the optimization potential of tensor line visualization for the design of ribbed plastic components.

At the end of the contribution still open questions and limitations of using tensorial data and visualization techniques will be addressed.

3.20 Kernel Distribution Embeddings: Applications to Diffusion MRI

Thomas Schultz (Universität Bonn, DE)

Joint work of Schultz, Thomas; Schlaffke, Lara; Schölkopf, Bernhard; Schmidt-Wilcke, Tobias
Main reference T. Schultz, L. Schlaffke, B. Schölkopf, T. Schmidt-Wilcke, "HiFiVE: A Hilbert Space Embedding of Fiber Variability Estimates for Uncertainty Modeling and Visualization," Computer Graphics Forum, 32(3pt1):121–130, 2013.
URL http://dx.doi.org/10.1111/cgf.12099

Recently, the popular and successful idea of using kernels to map individual points to feature spaces has been extended to produce feature space representations of probability distributions. This talk will provide a gentle introduction to this topic and explain how it naturally leads to a higher-order descriptor of the uncertainty in fiber directions estimated from diffusion MRI. I will show examples in which this novel descriptor is successfully applied for uncertainty visualization and for improved segmentation of gray matter structures such as the thalamus.

3.21 Mathematical Review of NMR Signal with Restricted Diffusion

Nir Sochen (Tel Aviv University, IL)

Joint work of Bar, Leah; Sochen, Nir; Morozov, Daria; Cohen, Yoram

We review the solution to the Bloch-Torrey equations via the Multiple Correlation Function (MCF) frame work. The single and double pulse field gradients are analysed via this framework. We show how one can use a direct extension of the MCF. The direct approach coincides with the indirect approach of Özerslan and Basser for certain geometries and extends it in the spherical case. An inverse process is applied to recover the geometric data. Experiments on phantoms with mixture of geometries are with good fit to the theory.

3.22 Diffusion Measurement Tensors

Carl-Fredrik Westin (Harvard Medical School – Boston, US)

Joint work of Westin, Carl-Fredrik; Knutsson, Hans; Nilsson, Markus

Diffusion MRI and NMR is one of the most dynamic and cutting-edge areas of imaging science and NMR physics, but the vast majority of applications focus on the simplest form of the basic experiment, the Stejskal-Tanner pulse sequences, which we refer to here as single pulsed field gradient (sPFG) experiment. sPFG typically is used to measure the mean diffusion (apparent diffusion coefficient, ADC) and diffusion anisotropy (Fractional Anisotropy, FA). Although current popular diffusion measures are very sensitive to changes in the cellular architecture, they are not very specific regarding the type of change. These measures provide crude markers of cellular disruption, since cell damage tends to break down semi-permeable cell walls increasing water mobility and thus the observed diffusivity.

We are at the cusp of a completely new generation of diffusion MRI technologies, which has the potential to transform what is possible with the technique via non-conventional underlying pulse sequences. The traditional sPFG sequence generates a diffusion measurement tensor of rank-1. We will review the family of new emerging technologies, and discuss how these techniques will allow for direct diffusion measurements of higher than rank-1.

3.23 Tensor Field Analysis: Some Open Problems

Eugene Zhang (Oregon State University, US)

Tensor fields have a wide range of applications in science, engineering, medicine, and image processing. There have been much work by the image processing, medical imaging, and scientific visualization communities, leading to vast amount of knowledge of 2D and 3D tensor fields.

In this talk, I would like to discuss a number of problems which I believe can provide critical insights on furthering our understanding of 3D tensor fields.

4 List of Previous Meetings in this Seminar Series

- The 2004 Dagstuhl Perspective Workshop "Visualization and Processing of Tensor Fields" (Perspectives Workshop 04172, April 2004, Organizers: Hans Hagen and Joachim Weickert) was the first international forum where leading experts on visualization and processing of tensor fields had the opportunity to meet, many for the first time. This workshop identified several key issues and triggered fruitful collaborations that have also led to the first book in this area. Springer book published in 2006: ISBN 978-3-540-25032-6.
- The 2007 Dagstuhl Seminar "Visualization and Processing of Tensor Fields" (Seminar 07022, January 2007, Organizers: David Laidlaw and Joachim Weickert) was equally successful and the progress reported in a second book published with Springer published in 2009: ISBN 978-3-540-88377-7.
- The 2009 Dagstuhl Seminar "New Developments in the Visualization and Processing of Tensor Fields" (Seminar 09302, July 2009, Organizers: Bernhard Burgeth and David Laidlaw) saw a shift in focus, and in addition to diffusion imaging, paid attention to engineering applications of tensors in fluid mechanics, material science, and elastography. Springer has also published a third book in this series: ISBN 978-3-642-27342-1.
- The 2011 Dagstuhl Seminar "Visualization and Processing of Tensors and Higher Order Descriptors for Multi-Valued Data" (Seminar 11501, December 2011, Organizers: Bernhard Burgeth, Anna Vilanova and Carl-Frederik Westin) focussed on modern and emerging methods for analysis and visualization of tensor and higher-order descriptors from medical imaging and engineering applications. The subject of the seminar series saw a shift where higher-order descriptors that went beyond tensors were explicitly addressed. The meeting resulted in a book that is at the moment of writing in the editorial stage, and is expected to be published around May 25 of this year.

5 Additional Outcomes of Previous Meeting

After meeting Gary Zhang at the Dagstuhl Seminar in 2011, Lauren O'Donnell and Thomas Schultz got involved in the organization of the following workshops:

- MICCAI 2012 Workshop on Computational Diffusion MRI, Nice, France.
- MICCAI 2013 Workshop on Computational Diffusion MRI, Nagoya, Japan.
- MICCAI 2014 Workshop on Computational Diffusion MRI, Boston, MA, USA.

The 2013 workshop resulted in the publication of the book Computational Diffusion MRI and Brain Connectivity (ISBN 978-3-319-02475-2) edited among others by Thomas Schultz and Lauren O'Donnell, and with contributions by a number of the attendees of the 2011 Dagstuhl Seminar.

Finally the seminar also resulted in a successful "Landesforschungsförderprogramm (LFFP) des Saarlandes" grant proposal.

6 Schedule

	Monday	Tuesday	Wednesday	Thursday	Friday
09:00	Introduction Breakout sessions	Nir Sochen (20) Ofer Paternak (20)	Tom Dela Haije (20) Cagatay Demiralp (30)	Markus Stommel + Marc Schöneich (40)	
09:30					Book Breakout summary
10:00	Thomas Schultz (20)				
10:30	Coffee Break				
11:00	Luc Florack (20)	Hans Knutsson (20)	Andrea Fuster (15)	Gerik Scheuermann (15)	Breackout summary
11:30	Ingrid Hotz (20)	C.-F. Westin (20)	Eugene Zhang (30)	G. Elisabeta Marai (15)	Goodbye
12:00	Lunch (12:15)				
12:30					
13:00					
13:30	Renato Pajarola(20)	Evren Ozerslan (20)	Social Event	Max Langbein (15)	
14:00	Guoning Chen (15)	Jos Roerdink (20)		Christoph Garth (15)	
14:30	Lauren O'Donnell (15)	Bernhard Burgeth(15)		Rodrigo Moreno (15)	
15:00					
15:30	Coffee Break			Coffee Break	
16:00	Breakout sessions	Breakout sessions		Breakout sessions	
16:30					
17:00					
17:30					
18:00	dinner				

Participants

- Bernhard Burgeth
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University of Houston, US
- Tom Dela Haije
TU Eindhoven, NL
- Çağatay Demiralp
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Report from Dagstuhl Seminar 14091

Data Structures and Advanced Models of Computation on Big Data

Edited by

Alejandro López-Ortiz[1], Ulrich Carsten Meyer[2], and Robert Sedgewick[3]

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Abstract

This report documents the program and the outcomes of Dagstuhl Seminar 14091 "Data Structures and Advanced Models of Computation on Big Data". In today's computing environment vast amounts of data are processed, exchanged and analyzed. The manner in which information is stored profoundly influences the efficiency of these operations over the data. In spite of the maturity of the field many data structuring problems are still open, while new ones arise due to technological advances.

The seminar covered both recent advances in the "classical" data structuring topics as well as new models of computation adapted to modern architectures, scientific studies that reveal the need for such models, applications where large data sets play a central role, modern computing platforms for very large data, and new data structures for large data in modern architectures.

The extended abstracts included in this report contain both recent state of the art advances and lay the foundation for new directions within data structures research.

Seminar February 24–28, 2014 – http://www.dagstuhl.de/14091
1998 ACM Subject Classification E.1 Data Structures, F.1 Computation by Abstract Devices, F.2 Analysis of Algorithms and Problem Complexity, G.2 Discrete Mathematics
Keywords and phrases data structures, big data, models of computation, I/O Model, sorting, quicksort, graph algorithms, hashing, compression, succinct data structures, trajectories, text search, GPU algorithms, MapReduce
Digital Object Identifier 10.4230/DagRep.4.2.129
Edited in cooperation with Timo Bingmann

1 Executive Summary

Alejandro López-Ortiz
Ulrich Carsten Meyer
Robert Sedgewick

A persistent theme in the presentations in this Dagstuhl seminar is the need to refine our models of computation to adapt to modern architectures, if we are to develop a scientific basis for inventing efficient algorithms to solve real-world problems. For example, Mehlhorn's presentation on the cost of memory translation, Iacono's reexamination of the cache-oblivious model, and Sanders' description of communication efficiency all left many participants

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questioning basic assumptions they have carried for many years and are certain to stimulate new research in the future.

Better understanding of the properties of modern processors certainly can be fruitful. For example, several presentations, such as the papers by Aumüller, López-Ortiz, and Wild on Quicksort and the paper by Bingmann on string sorting, described faster versions of classic algorithms that are based on careful examination of modern processor design.

Overall, many presentations described experience with data from actual applications. For example, the presentations by Driemel and Varenhold on trajectory data described a relatively new big-data application that underscores the importance and breadth of application of classic techniques in computational geometry and data structure design.

Other presentations which discussed large data sets on modern architectures were the lower bound on parallel external list ranking by Jacob, which also applies on the MapReduce and BSP models commonly used in large distributed platforms; and by Hagerup who considered the standard problem of performing a depth first search (DFS) on a graph, a task that is trivial in small graphs but extremely complex on "big data" sets such as the Facebook graph. He proposed a space efficient algorithm that reduces the space required by DFS by a $\log n$ factor or an order of magnitude on practical data sets.

Schweikardt gave a model for MapReduce computations, a very common computing platform for very large server farms. Salinger considered the opposite end of the spectrum namely how to simplify the programming task as to take optimal advantage of a single server which also has its own degree of parallelism from multiple cores, GPUs and other parallel facilities.

In terms of geometric data structures for large data sets Afshani presented sublinear algorithms for the I/O model which generalize earlier work on sublinear algorithms. Sublinear algorithms are of key importance on very large data sets, which are thus presumably unable to fit in main memory. Yet most of the previously proposed algorithms assumed that such large data sets were hosted in main memory. Toma gave an external memory representation of the popular quad tree data structure commonly used in computer graphics as well as other spatial data applications.

2 Table of Contents

3 Overview of Talks

3.1 Sublinear Geometric Algorithms in the I/O Model

Peyman Afshani (Aarhus University, DK)

Joint work of Afshani, Peyman; Matulef, Kevin; Wilkinson, Bryan

Being able to handle massive data is one of the main motivations to consider sublinear algorithms. Typically in these problems, the data is assumed to be stored in a standard representation and with no extra assumptions and thus with no extra preprocessing. The goal is to perform certain computational tasks in sublinear time, (i.e., without reading the whole input) and this is almost always done using a randomized algorithm. Despite the fact that the motivation comes from massive data, most of the previous results in sublinear algorithms were obtained in internal memory. We observe that building sublinear algorithms in the I/O model results in dealing with novel and interesting challenges. We introduce some new sublinear algorithms in the I/O model. These include, searching a linked list for an element, and detecting the intersection of two polygons. We prove that our results are optimal up to an extra log factor. Obtaining further sublinear algorithms in the I/O model is an obvious area left open by this work.

3.2 Distance Oracles for Large Real-World Graphs

Deepak Ajwani (Bell Labs – Dublin, IE)

Processing and analyzing massive real-world graphs rapidly has emerged as an important challenge in data analysis in recent years. Many important graph processing algorithms, such as p-center clustering, require computation of shortest-path distances between arbitrary numbers of node pairs in the graph. Since computation of exact distances between all node-pairs of an arbitrary large graph (e.g., 10 M nodes and up) is prohibitively expensive both in computational time and storage space, distance approximation is often used in place of exact computation. A distance oracle is a data structure that answers inter-point distance queries in $o(n^2)$ time and storage space, where n is the number of nodes in the graph. While there is a rich body of theoretical literature on approximate distance oracles with worst-case bounds, there are only a handful of (mostly recent) approaches that are known to provide strong approximation in practice on real-world graphs. In this talk, we present theoretical evidence that for many real-world graphs, with intrinsic small hyperbolicity structure, we can naturally leverage this topological feature to build a high fidelity distance approximation oracle. We show that such an oracle (i) can be constructed efficiently, (ii) requires $O(n)$ words of storage space and (iii) results in a small average additive distortion of distance.

3.3 RAM-Efficient External Memory Algorithms

Lars Arge (Aarhus University, DK)

In recent years a large number of problems have been considered in external memory models of computation, where the complexity measure is the number of blocks of data that are moved between slow external memory and fast internal memory (also called I/Os). In practice, however, internal memory time often dominates the total running time once I/O-efficiency has been obtained. In this talk we discuss sorting algorithms that are simultaneously I/O-efficient and internal memory efficient in the RAM model of computation. We also describe interesting open problems in particular in relation to batched geometric problems.

3.4 Optimal Partitioning for Multi-Pivot Quicksort

Martin Aumüller (TU Ilmenau, DE)

Joint work of Aumüller, Martin; Dietzfelbinger, Martin; Klaue, Pascal
Main reference M. Aumüller, M. Dietzfelbinger, "Optimal Partitioning for Dual Pivot Quicksort," in Proc. of the 40th Int'l Colloquium on Automata, Languages, and Programming (ICALP'13), LNCS, Vol. 7965, pp. 33–44, Springer, 2013.
URL http://dx.doi.org/10.1007/978-3-642-39206-1_4

This talk considers variants of classical Quicksort where k pivots are used to split the input into $k+1$ segments. This can be done in different ways, giving rise to different algorithms. In the first part of this talk, we consider Dual-Pivot Quicksort. We study three different algorithms which all achieve the lowest possible average comparison count w.r.t. to the leading term: $1.8\,n \ln n$. This improves on the average comparison count of $1.9\,n \ln n$ achieved by Yaroslavskiy's algorithm, the standard internal sorting algorithm in Java 7. The second part of this talk will consider generalizations which use more than two pivots. Surprisingly, preliminary results indicate that the average comparison count of optimal k pivot Quicksort almost coincides with the average comparison count achieved by Median-of-k Quicksort.

3.5 Semantic Search on Big Data

Hannah Bast (Universität Freiburg, DE)

I presented a demo of our prototype for semantic full-text search. It provides a deep integration of classical full-text search (in the demo: on the English Wikipedia) with search in knowledge bases (in the demo: Freebase). I the discussed five major challenges in the context of big data: (1) getting hold of big data, (2) making sense of big data, (3) fast query processing via tailor-made index data structures, (4) Quality Evaluation with Amazon Mechanical Turk, and (4) enabling reproducibility of results via a web application.

3.6 Parallel String Sorting with Super Scalar String Sample Sort

Timo Bingmann (KIT – Karlsruhe Institute of Technology, DE)

Joint work of Bingmann, Timo; Sanders, Peter
Main reference T. Bingmann, P. Sanders, "Parallel String Sample Sort," in Proc. of the 21st Annual European Symp. on Algorithms (ESA'13), LNCS, Vol. 8125, pp. 169–180, Springer, 2013.
URL http://dx.doi.org/10.1007/978-3-642-40450-4_15

We present the currently fastest parallel string sorting algorithm for modern multi-core shared memory architectures. First, we describe the challenges posed by these new architectures, and discuss key points to achieving high performance gains. Then we give an overview of existing sequential and parallel string sorting algorithms and implementations. Thereafter, we continue by developing super scalar string sample sort (S^5), which is easily parallelizable and yields higher parallel speedups than all previously known algorithms. For NUMA systems, we also given an outlook into parallel K-way LCP-aware merging of presorted sequences with LCPs.

3.7 Range Minimum Queries (Part II)

Gerth Stølting Brodal (Aarhus University, DK)

Main reference G. S. Brodal, A. Brodnik, P. Davoodi, "The Encoding Complexity of Two Dimensional Range Minimum Data Structures," in Proc. of the 21st Annual European Symp. on Algorithms (ESA'13), LNCS, Vol. 8125, pp. 229–240, Springer, 2013.
URL http://dx.doi.org/10.1007/978-3-642-40450-4_20

In the two-dimensional range minimum query problem an input matrix A of dimension $m \times n$, $m \leq n$, has to be preprocessed into a data structure such that given a query rectangle within the matrix, the position of a minimum element within the query range can be reported. We consider the space complexity of the encoding variant of the problem where queries have access to the constructed data structure but can not access the input matrix A, i.e., all information must be encoded in the data structure. Previously it was known how to solve the problem with space $O(mn \min\{m, \log n\})$ bits (and with constant query time), but the best lower bound was $\Omega(mn \log m)$ bits, i.e., leaving a gap between the upper and lower bounds for non-quadratic matrices. We show that this space lower bound is optimal by presenting an encoding scheme using $O(mn \log m)$ bits. We do not consider query time

3.8 ERa – A Practical Approach to Parallel Construction of Suffix Trees

Andrej Brodnik (University of Primorska, SI)

Joint work of Brodnik, Andrej; Jekovec, Matevž
URL http://lusy.fri.uni-lj.si/sites/lusy.fri.uni-lj.si/files/publications/era-dagstuhl_2014.pdf

The most frequently used data structure to answer queries *where* and *how often* a pattern appears in a preprocessed text is a suffix tree. Therefore, it is an important challenge to

design practically efficient algorithms to construct large suffix trees. Moreover, computers nowadays contain processors with 32 and even more cores, which, in case of human genome of length $n = 2.8\,\text{Gbp}$, represents essentially $\log n$ processors. In this contribution we analyze an efficient parallel algorithm called ERa (Elastic Range). In our presentation we first give a quick overview of known theoretically efficient suffix tree construction algorithms that are supplemented by a brief survey of suffix tree construction algorithms used in practice. The survey is followed by a more detailed presentation of ERa, currently the best known parallel algorithm for suffix tree construction in practice. A short theoretical analysis of ERa follows the presentation. The concluding part gives an experimental evaluation of ERa applied to a human genome. We show that the bottleneck for running time of the algorithm is indeed I/O and in particular writing the resulting suffix tree to the disk. We also show, that further improvements in scheduling of parallel construction of suffix subtrees is possible. We conclude with open challenges that include a design of theoretically efficient and practically fast algorithm.

3.9 Data Structures for Trajectories

Anne Driemel (TU Dortmund, DE)

Joint work of Driemel, Anne; Har-Peled, Sariel
Main reference A. Driemel, S. Har-Peled, "Jaywalking Your Dog: Computing the Fréchet Distance with Shortcuts," SIAM Journal on Computing, 42(5):1830–1866, September 2013.
URL http://dx.doi.org/10.1137/120865112

The Fréchet distance is a popular distance measure for trajectories of moving objects. It can be used for map-matching a trajectory to a street network, for finding similar subtrajectories and for clustering trajectories. So far, only few data structures have been proposed to support such operations efficiently. We develop several new tools: (a) a data structure for preprocessing a curve that supports $(1+\varepsilon)$-approximate Fréchet distance queries between a subcurve (of the original curve) and a line segment; (b) a near linear time algorithm that computes a permutation of the vertices of a curve, such that any prefix of $2k-1$ vertices of this permutation forms an optimal approximation (up to a constant factor) to the original curve compared to any polygonal curve with k vertices, for any $k > 0$; and (c) a data structure for preprocessing a curve that supports approximate Fréchet distance queries between a subcurve and query polygonal curve. The query time depends quadratically on the complexity of the query curve and only (roughly) logarithmically on the complexity of the original curve. To our knowledge, these are the first data structures to support these kind of queries efficiently.

3.10 Biased Search for Bounded Universes

Rolf Fagerberg (University of Southern Denmark – Odense, DK)

We consider the problem of performing predecessor searches in a bounded universe while achieving query times that depend on the distribution of queries. We obtain several data

structures with various properties: in particular, we give data structures that achieve expected query times logarithmic in the entropy of the distribution of queries but with space bounded in terms of universe size, as well as data structures that use only linear space but with query times that are higher (but still sublinear) functions of the entropy. For these structures, the distribution is assumed to be known. We also consider data structures with general weights on universe elements, as well as the case when the distribution is not known in advance.

3.11 High-Order Entropy Compressed Bit Vectors with Rank/Select

Johannes Fischer (TU Dortmund, DE)

We show how to compress bit-vectors to support efficient rank-queries (counting the number of ones up to a given point). Unlike previous approaches, which either store the bit vectors plainly, or focus on compressing bit-vectors with low densities of ones or zeros, we aim at low entropies of higher order, for example 101010...10. Our implementations achieve very good compression ratios, while showing only a modest increase in lookup time.

3.12 Space-Economical Depth-First Search

Torben Hagerup (Universität Augsburg, DE)

Joint work of Hagerup, Torben; Elmasry, Amr; Kammer, Frank

As part of a wider investigation of space-bounded RAM computation, we consider the special problem of depth-first search (DFS) on a RAM with a read-only input, a small working memory and a write-only output. The usual recursive DFS algorithm needs $\Theta(n \log n)$ bits of stack memory and $O(n + m)$ time to process an input graph with n vertices and m edges. We show how to reduce the number of bits of working memory needed to $O(n \log \log n)$ while preserving a linear running time. Alternatively, $O(n)$ bits suffice if a running time of $O((n + m) \log \log n)$ is acceptable, and a tradeoff between these two extremes is possible. The latter result depends on a dynamic dictionary for small universes.

3.13 Algorithms for Graph Connectivity Problems – Connectivity Augmentation, All-Pairs Minimum Cut, and Cohesive Subset Decomposition

Tanja Hartmann (KIT – Karlsruhe Institute of Technology, DE)

Challenges, results and open problems on three topics related to graph connectivity – planar k-regular connectivity augmentation, all-pairs minimum cut and Gomory-Hu trees in dynamic scenarios, and cohesive subset decomposition (which is similar to graph clustering problems).

3.14 Space-filling Curves for 3D Mesh Traversals

Herman J. Haverkort (TU Eindhoven, NL)

Two-dimensional finite element methods require repeated traversals of a mesh of squares or triangles. By processing the mesh elements in order along a well-chosen space-filling curve, one can avoid storing the mesh in complicated and cache-inefficient data structures: only a small number of stacks are needed. For three-dimensional meshes, however, known space-filling curves do not quite suffice. In this presentation I present our latest results on what desirable properties of such space-filling curves can and cannot be realized.

3.15 Path Queries in Weighted Trees

Meng He (Dalhousie University, CA)

Main reference M. He, J. I. Munro, G. Zhou, "Path Queries in Weighted Trees," in Proc. of the 22nd Int'l Symp. on Algorithms and Computation, LNCS, Vol. 7074, pp. 140–149, Springer, 2011.
URL http://dx.doi.org/10.1007/978-3-642-25591-5_16

This talk presents new results on several path queries in trees in which each node is assigned a weight value. This is motivated by the needs of the manipulation of tree-structured data such as XML trees and tree network topology. One such query is path counting, in which we are given an arbitrary query path defined by two nodes and a query weight range, and the goal is to count the number of nodes along this path whose weights are within the given range. We designed succinct data structures that can answer path counting in optimal time. More precisely, our structure occupies $nH(W_T) + o(n \lg \sigma)$ bits, where n denotes the number of nodes in the tree, $H(W_T)$ denotes the entropy of the node weights, and σ is the distinct number of weights, and answers queries in $O(\lg \sigma / \lg \lg n + 1)$ time. Several other path queries can be defined in a similar way, including path median, path min and path reporting, and we achieved new results for these problems. All these generalize queries in 2D point sets and arrays to trees. The above results are from three papers. The first two are co-authored by Meng He, J. Ian Munro and Gelin Zhou, and Timothy M. Chan is also a coauthor of the third article.

3.16 Does the Cache-Oblivious Model Make Any Sense?

John Iacono (Polytechnic Institute of NYU – Brooklyn, US)

Several limitations of the cache-oblivious model are presented, some well-known, and others less so. However, algorithms in the cache-oblivious model perform well because they lead to optimizing locality of reference. We then explore how one might want to more directly model a modern computer using locality of reference as a central paradigm.

3.17 The Parallel External Memory Complexity of List Ranking

Riko Jacob (ETH Zürich, CH)

Joint work of Jacob, Riko; Lieber, Tobias; Sitchinava, Nodari

We study the problem of list ranking in the PEM model. We present an $\Omega(\log^2 N)$ (for $P = M$, $N = MB$) lower bound for a non-standard variant of the problem. This variant is also difficult in the bulk synchronous parallel (BSP) and MapReduce models.

3.18 Faster Clustering via Preprocessing

Tsvi Kopelowitz (University of Michigan – Ann Arbor, US)

Joint work of Kopelowitz, Tsvi; Krauthgamer, Robert
Main reference T. Kopelowitz, R. Krauthgamer, "Faster Clustering via Preprocessing," arXiv:1208.5247v1 [cs.DS], 2012.
URL http://arxiv.org/abs/1208.5247v1

We examine the efficiency of clustering a set of points, when the encompassing metric space may be preprocessed in advance. In computational problems of this genre, there is a first stage of preprocessing, whose input is a point set M and a distance function $d(\cdot, \cdot)$; the next stage receives as input a query point set Q, and should report a clustering of Q according to some objective, such as 1-median, in which case the answer is a point $a \in M$ minimizing $\sum_{q \in Q} d(a, q)$. We design algorithms that solve such problems within $(1 + \varepsilon)$–approximation under standard clustering objectives like p-center and p-median, and are fast when the metric M has low doubling dimension. By leveraging the preprocessing stage, our algorithms achieve query time that is near-linear in the query size $n = |Q|$, and is (almost) independent of the total number of points $m = |M|$. Moreover, our preprocessing data structure supports updates to M, and its storage requirement is a truly linear $O(m)$ independent of the doubling dimension.

3.19 Multi-Pivot Quicksort: Theory and Experiments

Alejandro López-Ortiz (University of Waterloo, CA)

Joint work of Kushagra, Shrinu; López-Ortiz, Alejandro; Munro, J. Ian; Qiao, Aurick
Main reference S. Kushagra, A. López-Ortiz, A. Qiao, J. I. Munro, "Multi-Pivot Quicksort: Theory and Experiments," in Proc. of the 16th Workshop on Algorithm Engineering and Experiments (ALENEX'14), pp. 47–60, SIAM, 2014.
URL http://dx.doi.org/10.1137/1.9781611973198.6

The idea of multi-pivot quicksort has recently received the attention of researchers after Vladimir Yaroslavskiy proposed a dual pivot quicksort algorithm that, contrary to prior intuition, outperforms standard quicksort by a significant margin under the Java JVM. More recently, this algorithm has been analysed in terms of comparisons and swaps by Wild and Nebel. Our contributions to the topic are as follows. First, we perform the previous experiments using a native C implementation thus removing potential extraneous effects

of the JVM. Second, we provide analyses on cache behavior of these algorithms. We then provide strong evidence that cache behavior is causing most of the performance differences in these algorithms. Additionally, we build upon prior work in multi-pivot quicksort and propose a 3-pivot variant that performs very well in theory and practice. We show that it makes fewer comparisons and has better cache behavior than the dual pivot quicksort in the expected case. We validate this with experimental results, showing a 7–8 % performance improvement in our tests.

3.20 The Cost of Address Translation

Kurt Mehlhorn (MPI für Informatik – Saarbrücken, DE)

Joint work of Jurkiewicz, Tomasz; Mehlhorn, Kurt
Main reference T. Jurkiewicz, K. Mehlhorn, "The Cost of Address Translation," arXiv:1212.0703v2 [cs.DS], 2012.
URL http://arxiv.org/abs/1212.0703v2

Modern computers are not random access machines (RAMs). They have a memory hierarchy, multiple cores, and a virtual memory. We address the computational cost of the address translation in the virtual memory. Starting point for our work on virtual memory is the observation that the analysis of some simple algorithms (random scan of an array, binary search, heapsort) in either the RAM model or the EM model (external memory model) does not correctly predict growth rates of actual running times. We propose the VAT model (virtual address translation) to account for the cost of address translations and analyze the algorithms mentioned above and others in the model. The predictions agree with the measurements. We also analyze the VAT-cost of cache-oblivious algorithms.

3.21 When Less is More – Energy-Efficient Sorting

Ulrich Carsten Meyer (Goethe-Universität Frankfurt am Main, DE)

Joint work of Beckmann, Andreas; Meyer, Ulrich; Sanders, Peter; Singler, Johannes
Main reference A. Beckmann, U. Meyer, P. Sanders, J. Singler, "Energy-efficient sorting using solid state disks," in Sustainable Computing: Informatics and Systems, 1(2):151–163, June 2011.
URL http://dx.doi.org/10.1016/j.suscom.2011.02.004

The energy efficiency of data processing is becoming more and more important for both economical and ecological reasons. In this talk, we take sorting of large data sets as a representative case study for data-intensive applications. We review our system for the JouleSort competitions 2010/11. Guided by theoretical algorithmic considerations and taking practical limitations into account, we carefully chose the components for building an energy-efficient computer for this task. These decisions were backed up by performance and power measurements of several competing options. Finally, we chose a low-power Intel Atom 330 processor, supported by four solid state disks, which have little power consumption and provide high bandwidths. Our sophisticated implementation of the sorting algorithms did not only feature great CPU efficiency. By employing overlapping, it loads all available resources in parallel, resulting in a good overall balance between I/O and computation. Using this setup, we have beaten the former records in the JouleSort category of the well-established

Sort Benchmark for inputs from 10 GB to 1 TB of data, by factors of up to 5.1. This usually comes without a penalty in running time. We also speculate on the consequences of future hardware for the Sort Benchmark contest, and identify certain problems, also relating to the monetary cost of energy.

3.22 Outperforming LRU via Competitive Analysis on Parametrized Inputs

Gabriel Moruz (Universität Frankfurt, DE)

Main reference G. Moruz, A. Negoescu, "Outperforming LRU via Competitive Analysis on Parametrized Inputs for Paging," in Proc. of the 23rd Annual ACM-SIAM Symp. on Discrete Algorithms (SODA'12), pp. 1669–1680, SIAM 2012.
URL http://dx.doi.org/10.1137/1.9781611973099.132

Competitive analysis was often criticized because of its too pessimistic guarantees which do not reflect the behavior of paging algorithms in practice. For instance, many deterministic paging algorithms achieve the optimal competitive ratio of k, yet LRU and its variants clearly outperform the rest in practice. In this paper we aim to reuse and refine insights from the competitive analysis to obtain new algorithms that cause few cache misses in practice. We propose a new measure of the "evilness" of the adversary, which results in a parametrization of the input that we denote *attack rate*. This measure is based on the characterization of the optimal offline algorithm by Koutsoupias and Papadimitriou and uses the fact that a number of pages are for sure in its memory. We show that the attack rate r is a tight bound on the competitive ratio of deterministic paging algorithms and give experimental results which show that r is usually much smaller than the cache size k and thus provides more realistic upper bounds for the competitive ratio of existing algorithms. We use a priority-based framework, which always yields r-competitive algorithms regardless of the priority assignment. In this framework, LRU can be obtained under a certain priority assignment and is thus only one algorithm among many other r-competitive ones. Using the enhanced flexibility given by this framework, we give a priority policy which leads to an algorithm outperforming LRU, RLRU and other practical algorithms on a wide selection of real-world cache traces.

3.23 Succinct Data Structures for Representing Equivalence Classes

J. Ian Munro (University of Waterloo, CA)

Joint work of El-Zein, Hicham; Lewenstein, Mosche; Munro, J. Ian; Raman, Venkatesh

We examine the problem of representing (naming) n elements in an arbitrary set of equivalences so that given a pair of elements we can (quickly) determine whether they are in the same class. We also want the extra space required for the representation of these classes to be minimal. If no extra space (other than the value n) is permitted, then an address space of $n \ln n + O(n)$ is necessary and sufficient. If the name space is required to be $[n]$, then $\Theta(\sqrt{n})$ extra bits are necessary and sufficient for a representation. We give an $O(\lg n)$ time, $O(\sqrt{n})$ bit data structure and an $O(1)$, $O(\sqrt{n} \lg n)$ bit method. An efficient method of supporting

updates on the classes is also discussed. Finally we consider the situation in which the name space is relaxed a little to $O(n)$. For the name space $[2n]$ we give a constant time method requiring $O((\log n)^2)$ extra bits and one with name space $[4n]$ using $O(\lg n \lg\lg n)$ bits.

3.24 On the Energy Consumption of Sorting and Searching

Markus E. Nebel (TU Kaiserslautern, DE)

In this talk, based on the specification of the ARM CPU, we introduce a model for the energy consumption of programs being executed. Considering examples from sorting and searching, we show that, according to our model, a faster algorithm not always consumes less energy than a slower one. This observation most often holds for the average-case behavior on large inputs but sometimes is valid for the worst-case as well. This even remains true if so-called leakage power is taken into consideration. Many of our findings have been confirmed experimentally. Our study raises questions with respect to the design of energy efficient algorithms.

3.25 Lattice Compression

Patrick K. Nicholson (MPI für Informatik – Saarbrücken, DE)

In this talk I survey some recent succinct data structures for representing partial orders. I pose the problem of representing lattice orders, i.e., their Hasse diagrams, using space matching the information theoretic lower bound to within constant factors. The current best data structures occupy $O(n^{3/2} \log n)$ bits of space, whereas the information theoretic bound is $\Theta(n^{3/2})$ bits; the constant hidden by the theta is unknown. The core challenge is to represent a $K_{2,2}$-free bipartite graph using $\Theta(n^{3/2})$ bits of space, such that it can be determined, given two vertices, whether there is an edge between them.

3.26 Expected Linear Time Sorting for Word Size $\Omega(\log^2 n \log\log n)$

Jesper A. Sindahl Nielsen (Aarhus University, DK)

Sorting n integers in the word-RAM model is a fundamental problem and a long-standing open problem is whether integer sorting is possible in linear time when the word size is $\omega(\log n)$. In this paper we give an algorithm for sorting integers in expected linear time when the word size is $\Omega(\log^2 n \log\log n)$. Previously expected linear time sorting was only possible for word size $\Omega(\log^{2+\varepsilon} n)$. Part of our construction is a new packed sorting algorithm that sorts n integers of $\frac{w}{b}$-bits packed in $O(\frac{n}{b})$ words, where b is the number of integers packed in a word of size w bits. The packed sorting algorithm runs in expected $O(\frac{n}{b}(\log n + \log^2 b))$ time.

3.27 Gunrock: High-Performance, High-Level Iterative Graph Computation on GPUs

John Owens (University of California – Davis, US)

We are building Gunrock, a GPU library for bulk-synchronous programmable graph computation. Gunrock's goals are a high-level programming model with high performance. The implementation today includes fast load-balanced traversal and programmable operators and enactors to implement a (currently) small number of graph primitives: breadth-first search, connected component, betweenness centrality, single-source shortest path, and PageRank. We note interesting future problems in the directions of traversal (push vs. pull), idemponent vs. non- idempotent operators, an operator formulation, bipartite and mutable graphs, and scalability.

3.28 One Answer, Two Questions, and Some Very Old Slides

Rasmus Pagh (IT University of Copenhagen, DK)

Joint work of Pagh, Rasmus; Stöckel, Morten

The talk has three parts: (1) A new algorithm for sparse matrix multiplication in the I/O model. (Joint work with Morten Stöckel.) (2) Two intriguing questions on near-neighbor search that are part of a new ERC-funded project. (3) Revisiting a presentation that I gave at Dagstuhl 10 years ago in view of current hardware.

3.29 Encoding Top-k and Range Selection

Rajeev Raman (University of Leicester, GB)

Joint work of Davoodi, Pooya; Grossi, Roberto; Iacono, John; Navarro, Gonzalo; Rao, Srinivasa
Main reference R. Grossi, J. Iacono, G. Navarro, R. Raman, S. S. Rao, "Encodings for Range Selection and Top-k Queries," in Proc. of the 21st Annual European Symp. on Algorithms (ESA'13), LNCS, Vol. 8125, pp. 553–564, Springer, 2013.
URL http://dx.doi.org/10.1007/978-3-642-40450-4_47

Many applications that deal with big data make use of the low effective entropy of data structuring problems: it is possible to pre-process the input into a data structure that can answer queries without accessing the input, whose space usage is significantly smaller than the space usage of the input. A classical example is as follows: given an array A of n values, pre-process it to answer Range Maximum Queries (RMQ), which given two indices l and r, returns the position containing the maximium element in $A[l..r]$. It is known that there is a data structure of size $2n + o(n)$ bits that answers RMQ in $O(1)$ time, in contrast to the $O(n \log n)$ bits needed to store A itself. We consider generalizations of the RMQ problem with low effective entropy defined on an array A of values including: Range Top-2 (returning the positions of the largest and second-largest elements in a sub-range of A),

Range Top-k (returning the positions of the top k values in a sub-range of A) and Range Selection (returning the position of the k-th largest value in a sub-range of A, given the sub-range and the value k as parameters). The work on range top-k appeared in ESA. The work on range second max is to appear in the Philosophical Transactions of the Royal Society A journal and can be found on arXiv http://arxiv.org/abs/1311.4394.

3.30 Algorithms in the Ultra-Wide Word Model

Alejandro Salinger (Universität des Saarlandes, DE)

Joint work of Salinger, Alejandro; Farzan, Arash; López-Ortiz, Alejandro; Nicholson, Patrick K.
Main reference A. Farzan, A. López-Ortiz, P. K. Nicholson, A. Salinger, "Algorithms in the Ultra-Wide Word Model," University of Waterloo Technical Report CS-2012-21.
URL https://cs.uwaterloo.ca/research/tr/2012/CS-2012-21.pdf

The effective use of parallel computing resources to speed up algorithms in current multi-core and other parallel architectures remains a difficult challenge, with ease of programming playing a key role in the eventual success of these architectures. In this talk we consider an alternative view of parallelism in the form of an ultra-wide word processor. We introduce the Ultra-Wide Word architecture and model, an extension of the word-RAM model that allows for constant time operations on thousands of bits in parallel. Word parallelism as exploited by the word-RAM model does not suffer from the more difficult aspects of parallel programming, namely synchronization and concurrency. In practice, the speedups obtained by word-RAM algorithms are moderate, as they are limited by the word size. We argue that a large class of word-RAM algorithms can be implemented in the Ultra-Wide Word model, obtaining speedups comparable to multi-threaded computations while keeping the simplicity of programming of the sequential RAM model. We show that this is the case by describing implementations of Ultra-Wide Word algorithms for dynamic programming and string searching. In addition, we show that the Ultra-Wide Word model can be used to implement a non-standard memory architecture, which enables the sidestepping of lower bounds of important data structure problems such as priority queues and dynamic prefix sums.

3.31 Communication Efficient Algorithms

Peter Sanders (KIT – Karlsruhe Institute of Technology, DE)

Joint work of Sanders, Peter; Schlag, Sebastian; Müller, Ingo
Main reference P. Sanders, S. Schlag, I. Müller, "Communication efficient algorithms for fundamental big data problems," in Proc. of the 2013 IEEE Int'l Conf. on Big Data, pp. 15–23, IEEE, 2013.
URL http://dx.doi.org/10.1109/BigData.2013.6691549

Big Data applications often store or obtain their data distributed over many computers connected by a network. Since the network is usually slower than the local memory of the machines, it is crucial to process the data in such a way that not too much communication takes place. Indeed, only communication volume sublinear in the input size may be affordable. We believe that this direction of research deserves more intensive study. We give examples

for several fundamental algorithmic problems where nontrivial algorithms with sublinear communication volume are possible. Our main technical contribution are several related results on distributed Bloom filter replacements, duplicate detection, and data base join.

3.32 New Worst-Case Approaches in Robust Optimization

Anita Schöbel (Universität Göttingen, DE)

Analysis of algorithms and data structures is often a worst-case analysis. In mathematical optimization, worst cases are considered in the field of robust optimization. The two best known robustness concepts are strict robustness (see, e.g., Ben-Tal, Ghaoui and Nemirovski, 2009) and regret robustness (see, e.g., Kouvelis and Yu, 1997). Although well researched, they are not suitable for all types of problems which is due to their over-conservatism. Consequently, the robust optimization community is developing new robustness concepts, also dealing with worst cases, but in a less conservative way. Among these are adjustable robustness (Ben-Tal, Goryashko, Guslitzer, Nemirovski, 2003), Gamma-robustness (Bertsimas and Sim, 2004), light robustness (Fischetti and Monaci, 2009), and different versions of recovery robustness (Liebchen, Lübbecke, Möhring and, Stiller, 2009) (Goerigk and Schöbel, 2011). In my talk I review these concepts and discuss their applicability for the design and analysis of data structures and algorithms.

3.33 MapReduce Transducers: A Formal Model for Distributed Streaming Computations

Nicole Schweikardt (Goethe-Universität Frankfurt am Main, DE)

Joint work of Neven, Frank; Servais, Frederic; Schweikardt, Nicole; Tan, Tony

We study the expressiveness of MapReduce where reducers are restricted to the generic formalism of finite memory computations. We utilise the framework of register automata and define MapReduce Automata (MRA) and MapReduce Transducers (MRT). The only difference between MRT and MRA is on the reducer level: within an MRA, a reducer is a register automaton which makes one pass over its input, and which outputs a single bag of values depending on its final configuration. In contrast, within an MRT, a reducer makes two passes over the input: in the first pass the reducer acts like a register automaton while in the second pass, it acts like a transducer that for each input value, outputs a bag of values. We can prove the following: (1) MRTs are strictly stronger than MRAs; (2) MRTs cannot detect the presence of a triangle in a graph; (3) for bounded degree graphs, MRAs can check all first-order properties with modulo counting quantifiers; (4) MRTs can evaluate all semijoin algebra queries, while MRAs cannot; (5) within MRAs and MRTs there is a strict hierarchy w.r.t. the number of rounds.

3.34 Counting Arbitrary Subgraphs in Data Streams

He Sun (MPI für Informatik – Saarbrücken, DE)

Joint work of Kane, Daniel; Mehlhorn, Kurt; Sauerwald, Thomas; Sun, He
Main reference D. M. Kane, K. Mehlhorn, T. Sauerwald, H. Sun, "Counting Arbitrary Subgraphs in Data Streams," in Proc. of the 39th Int'l Colloquium on Automata, Languages, and Programming (ICALP'12), LNCS, Vol. 7392, pp. 598–609, Springer, 2012.
URL http://dx.doi.org/10.1007/978-3-642-31585-5_53

We study the subgraph counting problem in data streams. We provide the first non-trivial estimator for approximately counting the number of occurrences of an arbitrary subgraph H of constant size in a (large) graph. Our estimator works in the turnstile model, i.e., can handle both edge-insertions and edge-deletions, and is applicable in a distributed setting. Prior to this work, only for a few non-regular graphs estimators were known in case of edge-insertions, leaving the problem of counting general subgraphs in the turnstile model wide open. We further demonstrate the applicability of our estimator by analyzing its concentration for several graphs H and the case where the underlying graph is a power law graph.

3.35 Strings, Geometry, Special Cases...

Sharma V. Thankachan (Louisiana State University, US)

Main reference R. Shah, C. Sheng, S. V. Thankachan, J. S. Vitter, "Top-k Document Retrieval in External Memory," in Proc. of the 21st Annual European Symp. on Algorithms (ESA'13), LNCS, Vol. 8125, pp. 803–814, Springer, 2013.
URL http://dx.doi.org/10.1007/978-3-642-40450-4_68

Often times, many string indexing problems can be reduced to special geometric problems, for which efficient solutions may exists. We present several such examples. One of them is the shared constraint range reporting (SCRR) problem, which is a special $(2, 1, 1)$-range reporting query where a corner of the query rectangle touches the line $x = y$. Notice that any I/O-optimal data structure for processing a general $(2, 1, 1)$ query must take $\Omega(n \log n / \log \log n)$ space. However, our special query can be optimally handled using an $O(n \log \log n)$ space structure. The problem is motivated from string indexing problems for top-k queries.

3.36 An Edge Quadtree for External Memory

Laura I. Toma (Bowdoin College – Brunswick, US)

Main reference H. Haverkort, M. McGranaghan, L. Toma, "An Edge Quadtree for External Memory," in Proc. of the 12th Int'l Symp. on Experimental Algorithms (SEA'13), LNCS, Vol. 7933, pp. 115–126, Springer, 2013.
URL http://dx.doi.org/10.1007/978-3-642-38527-8_12

We consider the problem of building a quadtree subdivision for a set E of n non-intersecting edges in the plane. Our approach is to first build a quadtree on the vertices corresponding to the endpoints of the edges, and then compute the intersections between E and the cells in the subdivision. For any $k \geq 1$, we call a K-quadtree a linear compressed quadtree that

has $O(n/k)$ cells with $O(k)$ vertices each, where each cell stores the edges intersecting the cell. We show how to build a K-quadtree in $O(\text{sort}(n+l))$ I/Os, where $l = O(n^2/k)$ is the number of such intersections. The value of k can be chosen to trade off between the number of cells and the size of a cell in the quadtree. We give an empirical evaluation in external memory on triangulated terrains and USA TIGER data. As an application, we consider the problem of map overlay, or finding the pairwise intersections between two sets of edges. Our findings confirm that the K-quadtree is viable for these types of data and its construction is scalable to hundreds of millions of edges.

3.37 Of Motifs and Goals: Mining Trajectory Data

Jan Vahrenhold (Universität Münster, DE)

Joint work of Gudmundsson, Joachim; Thom, Andreas; Vahrenhold, Jan
Main reference J. Gudmundsson, A. Thom, J. Vahrenhold, "Of Motifs and Goals: Mining Trajectory Data," in Proc. of the 20th Int'l Conf. on Advances in Geographic Information Systems (SIGSPATIAL'12), pp. 129–138, ACM, 2012.
URL http://dx.doi.org/10.1145/2424321.2424339

In response to the increasing volume of trajectory data obtained, e.g., from tracking athletes, animals, or meteorological phenomena, we present a new space-efficient algorithm for the analysis of trajectory data. The algorithm combines techniques from computational geometry, data mining, and string processing and offers a modular design that allows for a user-guided exploration of trajectory data incorporating domain-specific constraints and objectives.

3.38 Dual-Pivot Quicksort – Asymmetries in Sorting

Sebastian Wild (TU Kaiserslautern, DE)

Joint work of Wild, Sebastian; Nebel, Markus
Main reference S. Wild and M. E. Nebel, "Average Case Analysis of Java 7's Dual Pivot Quicksort," in Proc. of the 20th Annual European Symp. on Algorithms (ESA'12), LNCS, Vol. 7501, pp. 825–836, Springer, 2012.
URL http://dx.doi.org/10.1007/978-3-642-33090-2_71

We review the history of Yaroslavskiy's dual-pivot Quicksort that is used in Oracle's Java library since Java 7 and show how asymmetries in the algorithm lead to fewer needed comparisons than in classic Quicksort. These asymmetries can be amplified by choosing pivots with a systematic skew.

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3 Sebastian Wild, Markus E. Nebel, Ralph Neininger. *Average Case and Distributional Analysis of Java 7's Dual Pivot Quicksort*. accepted for publication in ACM Transactions on Algorithms

3.39 The Link Assessment Problem of Low Intensity Relationships in Complex Networks

Katharina A. Zweig (TU Kaiserslautern, DE)

Many large network data sets are noisy and contain links representing low intensity relationships that are difficult to differentiate from false-positive, random interactions. This is especially true for high-throughput data from systems biology, large-scale ecological data, but also for Web 2.0 data such as product ratings by users. In these networks with false-positive and false-negative edges, it is possible to clean the data based on the principle of structural similarity which assesses the number of common neighbors between any two nodes. Using similarity indices to globally rank all possible node pairs links and choosing the top-ranked pairs, true-positive edges can be validated, missing edges inferred, and spurious observations removed. While many similarity indices have been proposed to this end, there is no conclusive decision on which one to use. In this article we first contribute benchmark sets for complex networks from three very different settings (e-commerce, systems biology, and social networks) to enable a quantitative performance analysis of classic node similarity measures. Second, we propose a new node similarity measure called z^* which is the only stable top performing similarity measure in all cases. A third contribution is the central insight that, instead of using a global ranking, the performance can be tremendously increased by choosing the highest ranked neighbors for each single node (local ranking). There are many open problems connected to this problem, starting from parallelizing the algorithms, expected number of common neighbors in random graphs, to space/time tradeoffs depending on the size of the input.

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Report from Dagstuhl Seminar 14092

Digital Evidence and Forensic Readiness

Edited by

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Abstract

The seminar on Digital Evidence and Forensic Readiness provided the space for interdisciplinary discussions on clearly defined critical aspects of engineering issues, evaluation and processes for secure digital evidence and forensic readiness. A large gap exists between the state-of-the-art in IT security and best-practice procedures for digital evidence. Experts from IT and law used this seminar to develop a common view on what exactly can be considered secure and admissible digital evidence.

In addition to sessions with all participants, a separation of participants for discussing was arranged. The outcome of these working sessions was used in the general discussion to work on a common understanding of the topic. The results of the seminar will lead to new technological developments as well as to new legal views to this points and to a change of organizational measures using ICT. Finally, various open issues and research topics have been identified. In addition to this report, open research issues will also be published in the form of a *manifesto* on digital evidence.

One possible definition for *Secure Digital Evidence* was proposed by Rudolph et al. at the Eighth Annual IFIP WG 11.9 International Conference on Digital Forensics 2012. It states that a data record can be considered secure if it was created authentically by a device for which the following holds:

- The device is physically protected to ensure at least tamper-evidence.
- The data record is securely bound to the identity and status of the device (including running software and configuration) and to all other relevant parameters (such as time, temperature, location, users involved, etc.)
- The data record has not been changed after creation.

Digital Evidence according to this definition comprises the measured value and additional information on the state of the measurement device. This additional information on the state of the measurement device aims to document the operation environment providing evidence that can help lay the foundation for admissibility.

This definition provided one basis of discussion at the seminar and was compared to other approaches to forensic readiness.

Additional relevant aspects occur in the forensic readiness of mobile device, cloud computing and services. Such scenarios are already very frequent but will come to full force in the near future.

The interdisciplinary Dagstuhl seminar on digital evidence and forensic readiness has provided valuable input to the discussion on the future of various types of evidence and it has build the basis for acceptable and sound rules for the assessment of digital evidences. Furthermore, it has established new links between experts from four continents and thus has set the foundations for new interdisciplinary and international co-operations.

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1 Executive Summary

Carsten Rudolph

This summary briefly recapitulates the outcomes of our seminar on digital evidence and forensic readiness. The main focus of the seminar was to work on a common cross-discipline understanding of notions of digital evidence and forensic readiness. In particular, technical notions in the view of IT security experts and the legal view were considered. Furthermore, relevance of differences in jurisdictions in different countries was also discussed.

The participants of the seminar came from 4 continents (Europe, U.S., Africa and Australia) and 12 countries. The group was a mix of experts from digital forensics, IT security, cyber security, archival sciences, criminal law, civil law, and cyber law. Thus, all relevant disciplines for digital evidence and forensic readiness were represented in the seminar, creating a perfect group for the task, but also a challenging communication environment that required good leadership in the interaction and discussions.

The main focus of the seminar was to develop a common view on what exactly can be considered secure and admissible digital evidence. The seminar was a first attempt to achieve progress towards this goal and therefore, a comprehensive coverage of the topic was not to be expected. Nevertheless, the international interest in the topic as well as the intensive discussions in the seminar show the relevance of the topic. The results of the seminar identify open issues in the area of digital forensics, but also proposes first substantial steps in the direction of establishing strong and internationally useful notions for digital evidence and forensic readiness.

Initial talks and discussions quickly revealed some of the majour challenges:

- The growing variety of types of potential digital evidence increases the problem to define clear technical guidelines for the collection and evaluation of data records for forensic use. Examples include mobile devices, data stored and processed via cloud service, huge infrastructures with distributed data, or big data with many possible interpretations of data found.
- In many cases, digital evidence cannot be directly related to data on one device. In particular in cloud environments, stored data is distributed over different countries and digital processes easily cross borders. Thus, digital evidence becomes a cross-jurisdictional issue that needs rules on how to deal with differences and contradictions in jurisdiction.
- Teaching and education is another challenge. One cannot expect all lawyers, attorneys, or judges to become experts on technical issues. however, a basic understanding of the area of digital evidence is essential to be able to decide if expert witnesses are required and also to be able to achieve correct interpretations of the report by expert witnesses.

- forensic readiness can guide the development of systems that collect, store, and provide secure digital evidence. However, the applicability of forensically ready technical solutions is restricted by privacy and also economy. Here, processes need to be defined and adequate procedures and regulations (also internationally) need to be found.

Four discussion groups were formed in the seminar to discuss *digital forensic readiness processes and procedures for investigators*, *notions of digital evidence*, *a forensic readiness landscape*, and *forensic readiness: evidence in a digital world*. More details of the results of the discussions in the working groups can be found in the sections below.

As one of the major results of the seminar can be identified that all participants understood and agreed on the need to initiate future research activities in the area of digital evidence and forensic readiness. The results also clearly show that this research must be international and inter-disciplinary. Furthermore, the seminar has proven that technically oriented IT security experts and experts from law can co-operate to advance the state of the art. The seminar has established new inter-disciplinary and international contacts that are suitable to build a new community that will drive this strand of work in the field of forensic readiness.

2 Table of Contents

3 Overview of Talks

3.1 Legal Processes for Cloud Forensic Investigations

Aaron Alva (University of Washington – Seattle, US)

Cloud forensics is an emerging field that addresses how to ensure cloud-based evidence can be used in courts of law. The US Federal Rules of Evidence were originally designed for paper documents, and updates to the rules have yet to consider the cloud-paradigm. This presentation discusses the legal challenges involved in cloud computing investigations, and the potential legal processes that can be adapted for the admissibility of cloud-based evidence.

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1 A. Alva, and B. Endicott-Popovsky, *Legal Process and Requirements for Cloud Forensic Investigations, Cybercrime and Cloud Forensics: Applications for Investigation Processes*, IGI Global, 2013, pp.186–235; http://ssrn.com/abstract=2197978

3.2 Implementation guidelines for a harmonised digital forensic investigation readiness process model

Hein Venter (University of Pretoria, ZA)

Joint work of Valjarevic, Aleksandar;
Main reference A. Valjarevic, H. S. Venter, "Implementation guidelines for a harmonised digital forensic investigation readiness process model," in Proc. of the 2013 Information Security for South Africa Conf., pp. 1–9, IEEE, 2013.
URL http://dx.doi.org/10.1109/ISSA.2013.6641041

Digital forensic investigation readiness enables an organisation to prepare itself in order to perform a digital forensic investigation in a more efficient and effective manner. Benefits of achieving a high level of digital forensic investigation readiness include, but are not limited to, higher admissibility of digital evidence in a court of law, better utilisation of resources (including time and financial resources) and higher awareness of forensic investigation readiness.

The problem that this research addresses is that there exists no harmonised digital forensic investigation readiness process model. In addition, no implementation guidelines exist and, thus, there is a lack of an effective and standardised implementation of digital forensic investigation readiness measures within organisations.

Part of this research also involves the harmonasation and standardisation of the entire digital forensic investigation process. An ISO standard, ISO/IEC 27043, in this regard will be published in 2014 of which I am the main editor.

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3.3 Computer Forensics in Industrial Control Systems

Heiko Patzlaff (Siemens – Munich, DE)

This talk addresses the challenges of performing computer forensic investigations in industrial control systems (ICS). Starting with Stuxnet, the general lack of tools and procedures for analyzing security incidents in industrial settings has become apparent.

In this talk first an introduction to ICS systems is given. We discuss the challenges that arise when one needs to investigate security incidents in industrial products. In particular, what data is available in these systems, how to acquire this data, how to transfer and analyze it and what conclusions can be drawn from it. Some examples of real world cases are discussed. And the preliminary results of the Crisalis research project are presented that aims at developing tools and approaches for performing computer forensic investigations in IC systems.

3.4 The origin of digital evidence

Felix C. Freiling (Friedrich-Alexander-University Erlangen-Nürnberg, DE)

Joint work of Freiling, Felix C.; Dewald, Andreas
Main reference A. Dewald, F. C. Freiling, "Is Computer Forensics a Forensic Science?", Presentation at the 2012 Current Issues in IT Security Conf., Freiburg, Germany, 2012.

The focus of forensic computing , i.e., forensic computer science, is digital evidence. Digital evidence is any digital data that has relevance to questions of law. In this sense, digital evidence is similar to physical evidence, a type of evidence that is in the focus of classical forensic sciences (like forensic biology or forensic medicine). Unlike physical evidence, digital evidence is not primarily tied to the physical matter (e.g., the magnetic tape) that stores the data. The value of digital evidence regularly lies in the *information* encoded within the stored data. In cases where the physical storage device is important (e.g., the hard disc of a particular computer seized in a particular place), we have a combination of physical and digital evidence.

The fact that digital evidence is a question of information rather than physical matter is not surprising, since digital data is always an *abstraction* of physical phenomena (e.g., magnetization of the surface of a hard disc). But this aspect is also not specific to *digital* evidence. Here we can also draw from insights in classical forensic sciences: The notion of digital evidence can draw almost fully from what is called *imprint evidence*. Examples of imprint evidence are tool marks or footprints where – at least theoretically – an exchange of physical matter does not have to happen. And while for a long time the transfer of physical matter was believed to be the basis for any form of evidence (due to Locard's "exchange principle"), Inman and Rudin [1] developed the concept of "transfer of traits" to explain the origin of such evidence.

So digital evidence is not fundamentally new (as postulated by many authors, e.g., Casey [2]). The main difference between digital and physical evidence lies rather in the possibility to automatically gather and process it.

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3.5 Cloud and mobile forensics

Kim-Kwang Raymond Choo (University of South Australia – Mawson Lakes, AU)

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As the use of information and communications technologies (ICT) grows throughout society in general, so does their use by criminals, particularly in areas of serious and organised crime where ongoing secure communication and secure dissemination and storage of their data is critical for the operation of the criminal syndicate – similar to how cybercrime may be understood as a new way of committing traditional crimes ([5]; [7]).

There are various challenges and implications of emerging technologies for governments – particularly law enforcement and regulatory agencies – and other key stakeholders. For example, during investigations of crimes involving the use of cloud computing, there is usually some accumulation or retention of data on a digital device (e.g. mobile device used to access cloud services and cloud datacentres) that will need to be identified, preserved, analysed and presented in a court of law – a process known as digital forensics ([4]; [10]; [16]). Many conventional forensic tools have focused upon having physical access to the media that stores the data of potential interest. However, in a cloud computing environment it is often not possible or feasible to access the physical media that stores the user's data ([12]; [11]). In addition, [16] pointed out not all countries have legal provisions which allow for data to be secured at the time of serving a warrant, such as at the time of a search and seizure undertaking. Data fragmentation and distribution across the globe within numerous datacentres also present technical and jurisdictional challenges in the identification and seizure of (the fragile and elusive) evidential data by law enforcement and national security agencies in criminal investigations as well as by businesses in civil litigation matters ([7]; [14]; [15]). The technical and legal uncertainties surrounding these questions are, perhaps, why traditional boundaries are now blurred ([9]).

Existing digital forensic techniques are designed to collect evidential data from typical digital devices (e.g. where advanced security features and anti-forensic techniques are rarely exploited to their full extent). In contrast, serious and organised criminals often make use of secure services and devices specifically designed to evade legal interception and forensic collection attempts. Examples of devices designed to enable encrypted communications include the Android-based Blackphone ([3]; [19]) and the well-known BlackBerry. While the use of BlackBerry in the consumer market might be declining, Australian law enforcement agencies have suggested that these devices have become popular amongst serious and organised criminals – see interview by Acting CEO of Australian Crime Commission ([1]). For example, it was recently reported that

> *[t]housands of encrypted phones are believed to be in Australia and the officials say some of the phones are suspected of being used to send the most dangerous messages imaginable – those that lead to murder . . . [and] Police believe one*

of Australia's most violent outlaw bikers used uncrackable encrypted phones to order some of the shootings that have rocked Sydney ([2]).

Therefore, the digital forensics 'space' can be seen as a race, not only to keep up with hardware and software/application releases (e.g. by cloud and mobile service providers), but also from software and hardware modifications made by end users, particularly serious and organised criminals, to complicate or prevent the collection and analysis of digital evidence. For example, although cloud computing may have attracted academic attention, including issues relating to data sovereignty and data confidentiality, and the inadequacy of our existing legislative and regulatory frameworks to protect the data from criminals and government's prying eyes (see [5]; [6]; [8]; [13]; [17]; [18]), research on security, privacy and forensics challenges associated with cloud computing is still in its infancy.

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3.6 Forensic readiness for smart mobile devices

Florian Junge (Universität Bremen, DE)

Smart mobile devices (SMD), such as smartphones or tablets, offer a wide range of computation and communication facilities. Even though the devices were initially targeted for the private customer market, business organizations nowadays use them more frequently for commercial purposes. With a higher rate of usage, the devices become a more attractive target for attackers. However, even their restricted operating system designs cannot enforce comprehensive protection for the data on the device. Thus after the occurrence of a security incident, computer forensics techniques are needed for an understanding of the details, clean up and especially for a judicial prosecution. To facilitate forensic investigations, the concept of Forensic Readiness was developed. Its comprises measures to collect credible digital evidence, which might help in forensic investigations, as well as staff training for special procedures needed to shorten the investigations.

As part of an ongoing research project "SAiM", I examined the adaptation of forensic readiness to SMDs. I call this concept "Mobile Forensic Readiness", which has been presented in this talk. The focus is on smartphones in business organizations, because these have the biggest need for regulatory compliance in their operations. Therefore they need a proper analysis of security incidents and an effective collaboration with law enforcement. The research revealed potential technical, operational and legal aspects which have be addressed in order to achieve mobile forensic readiness.

On the technical side, topics like logging overhead or secure storage and transportation have to be considered. Also, data handling and hand over operations done by interal staff must be taken into account and which laws regarding privacy of personal data apply. Furthermore, as the data is designated to be used in court, its usefulness in such cases must be evaluated. My work examines these topics and the mentioned aspects. The goal is to deliver an approach to handle the overall process, beginning from risc assessments inside an organization to the handling of the evidence in court.

The technical architecture of this research work extends the components developed in SAiM. The project provides a framework for dynamic malware analysis on SMDs. Pattern matching algorithms for strings are used on the device itself. These use as input discretized events that are generated by various sensors throughout the operating system. A central server generates the patterns, because the computational power of a handheld device is not strong enough for the creation. The overall goal of this bi-polar approach in combination with a light-weight transport protocol is the recognition of designated malware as well as attacked apps.

3.7 Hardware-based secure digital evidence

Nicolai Kuntze (Fraunhofer SIT – Darmstadt, DE)

Joint work of Kuntze, Nicolai; Rudolph, Carsten

Traditional approaches to digital forensics are concerned with the reconstruction of events within digital systems that often are not built for the creation of evidence. Various examples exist where devices are meant to provide certain evidence like precise farming, speed cameras, automotive black boxes or other process documentation equipment. In these cases, specialised equipment samples data that is meant to provide a non-reputable proof on a certain event.

The presentation focuses on the idea of incorporating requirements for forensic readiness designing-in features and characteristics that support the use of the data produced in these devices being used as evidence. This paper explores legal requirements that such evidence must meet as the basis for developing technical requirements for the design of such systems. An approach is proposed using state of the art security technology that could be used to develop devices and establish processes crafted for the purpose of creating digital evidence. The aim hereby is to add specific meta data to the evidence created that shows additional specifics of the device, software and processes in place needed to judge on the authenticity of the evidence created.

The presenter suggests that the legal view needs to be incorporated into the device design as early as possible to allow for the probative value required of the evidence produced by such devices.

3.8 Can an Integrated Model of Digital Forensics Practice and Digital Records Lifecycle Inform Forensic Readiness

Corinne Rogers (InterPARES Trust – Vancouver, CA)

Main reference C. Rogers, "Digital Records Forensics: Integrating Archival Science into a General Model of the Digital Forensics Process," in Proc. of the Second Int'l Workshop on Cyberpatterns: Unifying Design Patterns with Security, Attack and Forensic Patterns, pp. 4–21, Oxford Brookes University, 2013.
URL http://tech.brookes.ac.uk/CyberPatterns2013/

Both archival and digital forensics methods and principles evolved out of practice and grew into established professional disciplines by developing theoretical foundations, which then returned to inform and standardize that practice. An intersection of digital forensics and digital diplomatics increase our capacity to identify records in digital systems, assess their authenticity, and establish the requirements for their long-term preservation. This paper presents the Digital Records Forensics general process model (DRF model), developed as a tool to aid in meaningful comparison of digital forensics activities and archival preservation activities. The purpose is to assess the moments in which digital records as understood by archival science, and digital evidence as understood by digital forensics, may be identified, their authenticity assessed, their reliability and integrity managed and preserved, in order to satisfy laws of evidence and requirements for admissibility.

The Digital Records Forensics general process model offers a point of departure in a mutual discussion between records professionals and digital forensics professionals. By combining

the technical expertise of digital forensics with the social and contextual analysis of records and data from archival science (and in particular the theory and methodology of archival diplomatics), a richer understanding of digital evidence is possible. This work continues in the research undertaken by the InterPARES Trust project (www.interparestrust.org) broadly, and in specific project within that research in which the author is involved that are studying metadata requirements for authenticity of digital material, and modeling of authenticity in the process of digital preservation of records and data in online environments.

3.9 Digital Evidence and Forensics in Australia and New Zealand – Recent Developments

Nigel Wilson (University of Adelaide, AU)

Recent cases in Australia and New Zealand demonstrate that digital evidence continues to present challenges at the pre-trial stage and also significant admissibility concerns. Discovery protocols have also had both procedural and trial impact as has inadequate compliance with digital evidence procedures. Most importantly, the role of expert evidence (and the increasing role of digital experts) has been paramount. Digital expert evidence faces a trio of challenges: its 'leading-edge' nature, the inherent complexity of the characteristics of digital evidence and the technical diversity of the sciences which constitute its specialised knowledge base. Future developments will involve issues arising from Australia's implementation of the European Convention on Cybercrime, cloud computing and human rights (principally privacy). As a result of the adoption of international cybersecurity obligations in Australia, mutual assistance will be required by law enforcement agencies and industry to expedite the interception, real-time collection, access to, preservation and disclosure of digital evidence.

3.10 Computational Forensics: Forensic Investigations in Cyberspace: what about big data?

Katrin Y. Franke (Gjøvik University Colledge, NO)

Information Society has become a reality with the establishment of the Internet. These ICT infrastructures are complex, rapidly growing, and constantly changing. Massive amounts of data are shared. The estimate for 2012 is 247 billion emails per, about 234 million websites and 5 billion mobile-phone users. The data volume is expected to increase by factor 44 within one decade only, i.e. from 800,000 petabyte in 2009 up to 35 zetabyte in 2020 (Gantz & Reinsel, 2010).

The reliance on the Internet creates increasing vulnerabilities. Cyber attacks from organized crime and terrorism pose severe threats to society. ICT infrastructures are constantly exposed to hostile and unwanted activities. In 2012 it was reported about 1 million victims of cyber crime with constant increase and expected losses of 297 billion Euros by 2017 (RAND, 2012).

The methods used to combat the increasing amount of high-tech crime and computer crime, must be improved. The amount of data and sharing of ICT resources through the cloud is so extensive and complex that current methods are incapable to cope. Proactive, ultra-large scale forensic investigations need to be researched and developed.

Computational forensics (CF) is an emerging interdisciplinary field of research. It unites expertise from computer science and forensic science. Data-science methods may establish decentralized, collaborative and independent investigation procedures. These require computing algorithms that are context- aware, adaptable and self-organizing. Typical challenges in investigations are about gathering evidence, search, ability to link various evidence and to visualize them.

In addition to the technological issues are the social and socio-technical, e.g. when it comes to culture, social behavior, law and policy rules in different countries. International cyber laws should be further improved so that international cooperation can strengthened. There is great demand to establish a legal framework for ICT (Sunde, 2006), and implement the law into ICT functionality, e.g. programming laws and regulations to automate the enforcement of them (Sunde, 2010).

The objective of this resentation is to provide an introduction to research methods through the increase of very large amounts of data, and to encourage discussion about the consequences thereof. Researchers in computer science and computer specialists be exposed with forensic sciences. Investigations related challenges that make it necessary to develop the next generation digital investigations, are pointed out. Researchers in forensics and case investigators are introduced to the basic techniques of digital computing and information technology.

Selected examples of successful methods adopted for data processing, and ongoing research will contribute to the understanding and confidence in the new technology. Examples include digital forensics through the cloud, i.e.

1. detection malicious PDF
2. the detection of malware when the malicious program operates, and
3. automatic linking evidence from multiple computers.

3.11 Models for Incorporating Forensic Readiness into Design as an Aspect of Resilience and Security

Barbara Endicott-Popovsky (University of Washington – Seattle, US)

Main reference B. Endicott-Popovsky, D. Ryan, D. Frincke, "The New Zealand Hacker Case: A post mortem," in Proc. of the Oxford Internet Institute Cybersafety Conf. on Safety and Security in a Networked World: Balancing Cyber-Rights & Responsibilities, 9pp., 2005.

URL http://www.oii.ox.ac.uk/microsites/cybersafety/extensions/pdfs/papers/barbara_endicottpopovsky.pdf

A typical incident response pits technicians against networks that aren't prepared forensically [1, 2]. If practitioners do consider collecting digital forensic data from networks, they face a choice between expending extraordinary effort (time and money) collecting forensically sound data, or simply restoring the network as quickly as possible. The latter means key evidentiary files most likely are altered in the process, limiting their forensic value. With limited interest in pursuing legal action, those administering networks most often make the expedient choice – responding to distraught users by restoring network function as soon as possible, ignoring the rigors of collecting and preserving forensically sound data [3].

In the interest of establishing evidence of having exercised reasonable care to protect data on their networks, legal counsel have begun urging organizations to invest in procedures and technology that will allow collection of forensically sound data defensible in a court of law [4].

There is an urgency to 're-think' our traditional models for incident response to include forensic readiness [1]. In this presentation a proactive and preventive approach as opposed to a reactive one. It includes recommendations for how to "operationalize" organizational forensic readiness and change our mental models for managing networks.

References

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3.12 Exploring the space of digital evidence

Carsten Rudolph (Fraunhofer SIT – Darmstadt, DE)

Digital evidence is much more than what is acquired during forensic investigations. One approach towards defining the available space for digital evidence suggests three dimensions. First, and most obviously, is the time when data is collected, processed, retained and correlated for potential forensic use. This dimension includes data collected at runtime, data collected for particular transactions, in case of deviations, for incidents, "post-mortem" forensic investigations, and the digitalization of evidence for court procedures. The second dimension describes the goal for which digital evidence is produced. This can be either for showing compliance, i.e. for proving that somebody was not responsible for some incident or for for showing malicious events that happened and to find who did what. Finally, the third dimension consists of the actual information to be documented. Examples are the documentation of the normal system behaviour, compliance information, accidents, safety issues, malicious behaviour, identity informations and various relevant parameters.

3.13 New "E-Justice" Law in Germany since 2013 – A Temple Architecture for an "Agenda of Securitization"

Viola Schmid (TU Darmstadt – Darmstadt, DE)

This abstract summarizes inspirations and discussions of an ambitious Dagstuhl seminar. The talk (27.02.2014) was titled: "New 'E-Justice' Law in Germany since 2013 – A Temple Architecture for an 'Agenda of Securitization"'. The presentation provided and argued with

[1] Defined as 'maximizing the ability of an environment to collect credible digital evidence while minimizing the cost of an incident response' [2].

Anglo-Saxon as well as German **terminologies** – partly bilingually. The importance of transnational terminologies is also reflected in the ductus of this abstract, by using German and Anglo-Saxon terminologies and texts. Examples for the results of this terminological query are:

- "Recht" as part of "Ge(recht)igkeit";
- "E-Justiz" instead of "E-Justice" and
- "Rechtswissenschaft" in the German terminology as "creation of legal science ("Rechtswissen")" instead of "legal science" in the Anglo-Saxon terminology describing the status of knowledge (Latin: scientia – "Wissen"). In short: A literal interpretation of "Rechtswissenschaft" comprises the process of information gathering ("Schaffen"). This inclusion of the scientific process (and method) makes the German denomination noteworthy.

These insights can only be gained by using "transnational" terminologies and legal analysis.

E.g.: This research method led to a differentiated use of "E-Justice" in the German legal system.[2]

These questions of terminology prepare the groundwork for the presentation of the following content that was addressed in February 2014:

- On the one hand – first – the audience was informed about new "E-Justice" ("E-Justiz") legislation in Germany and the challenges arising from this endeavor.
- On the other hand – second – a research initiative at the Faculty of Law and Economics, Technical University Darmstadt, Germany, was introduced (the so called "LEXONOMICS")[3].

In addition to the presentation at Dagstuhl, this abstract provides a third aspect: The follow-up – third – of the ideas presented in February 2014 with *the judgment of the European Court (Grand Chamber), 8. April 2014, C-293/12 and C-594/12* (Digital Rights Ireland Ltd (C-293/12) v Minister for Communications, Marine and Natural Resources et al. and Kärntner Landesregierung (C-594/12) et al.).

First: New "E-Justice" Law in Germany and Challenges for "Securitization" (Versicherheitlichung). The international audience with technological and/or legal expertise learned that there is a new German Law[4] in 2013 containing a master plan for lawmakers, as well as courts, establishing milestones for "e-courts" and "e-lawyers" [5] (especially the so called "power users"[6]) until 2022. By then, the "power users" must submit their briefs and documents "electronically" – otherwise the courts and the "justice system" may not admit these documents to court proceedings ("Informationstechnologiezwang" [7]). In short: There will be a new jurisdiction – the electronic jurisdiction ("elektronischer Rechtsweg") for law professionals[8] in Germany. Especially from the perspective of a German legal scientist ("Rechtswissenschaftler/in"), this digitization of the justice system poses new challenges

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[2] Soon to be published: V. Schmid, in: H. Sodan/J. Ziekow, Großkommentar zur Verwaltungsgerichtsordnung, 4th Edition 2014, § 173 marginal number 13.

[3] V. Schmid, in: H. Sodan/J. Ziekow, § 173 marginal numbers 10 and 57.

[4] Act to Promote Electronic Legal Transactions with the Courts (translation by the author) – Gesetz zur Förderung des elektronischen Rechtsverkehr mit den Gerichten ("FeRGG", acronym by V. Schmid, in: H. Sodan/J. Ziekow, § 173 marginal number 1) vom 10.10.2013, BGBl. I, S. 3786.

[5] And „e-administration" (Gesetz zur Förderung der elektronischen Verwaltung (E-Government-Gesetz – EGovG) vom 25. Juli 2013 (BGBl. I S. 2749).

[6] V. Schmid, in: H. Sodan/J. Ziekow, § 55a marginal number 25.

[7] V. Schmid, in: H. Sodan/J. Ziekow, § 55a marginal number 28.

[8] Not for ordinary citizens if there is no statutory requirement to be represented by a lawyer ("Anwaltszwang").

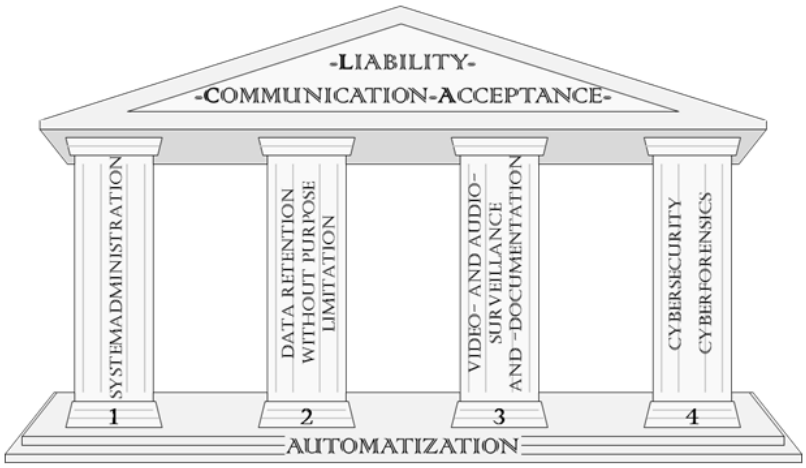

Figure 1 Temple architecture of e-justice.

that need be mastered. The German language differentiates between "Recht" (law) and "Gerechtigkeit" (justice, justness) and the question arises: How does the digitization affect this distinction? What is the difference between a "justice system" and an "e-justice-system"? This is not only a challenge for the German Legal System as the wise deliberations of M. de Boer-Buquicchio have demonstrated:

> "E-Justice, in my view, can stand for equitable justice; it can stand for efficient justice, or even for enlightened justice, but certainly not for electronic justice. What makes justice just, after all, is human judgment, applying a democratically accepted set of abstract rules to a specific situation. This can be greatly helped, but cannot be replaced by information technology, so I would prefer to speak about e-courts, rather than e-justice."[9]

The presentation took these arguments into account by stipulating that, in Germany, we should write and speak about "E-Justiz" ("E-Rechtsstaat") instead of using the Anglo-Saxon term "E-Justice". The reason being that using the terminology "E-Justice" in the German legal system could be understood as "E-Gerechtigkeit". The queries of terminology prepare for further challenges. "E-Justiz" demands new scientific approaches including applied sciences as well as legally compatible pragmatism ("rechtserträglicher Pragmatismus"). There are new threats and challenges – as well as opportunities and advantages – for the judicial system that are connected with the use of information technology.[10] A systematic analysis of potential weaknesses is the first step to achieving an equal chance for justice in the traditional court system, as well as in an e-court (E-Justiz) system. This agenda is titled with the term "securitization" ("Versicherheitlichung") – knowing that there are other notions of "securitization" e.g. in political sciences or in economics.[11] In a nutshell: In order to use the advantages of information technology in such a data sensitive system as "E-Justiz" "we" should identify the homework for the lawmakers, as well as courts and lawyers. Hence, the temple architecture shown in Figure 1 was presented and its publication (with more detailed information than in this in short article) in May 2014 was announced:[12]

[9] V. Schmid, in: H. Sodan/J. Ziekow, § 173 marginal number 13 with further reference.
[10] E.g. "mobile justice" ("M-Justiz"), V. Schmid, in: H. Sodan/J. Ziekow, § 55a marginal number 9.
[11] Further research and publications are initiated.
[12] V. Schmid, in: H. Sodan/J. Ziekow, § 55a marginal number 106.

The roof of this temple needs jurisprudential deliberations (even if there should be regulation at all ("Grenzen des Rechts")) about the liability (accountability, responsibility) of "E-Justiz"-providers; about the communication of technological changes within the system (such as "Rechtsbehelfsbelehrung"[13], § 58 VwGO[14]) and about instruments that encourage and inform the "clients" (and in the future perhaps customers as well as patrons) of the "E-Justiz"-system (acceptance). The columns of this temple symbolize new challenges for technology as well as law: Such as challenges for (the law on) system administration, data retention without purpose limitation, video and audio surveillance and documentation and – last but not least – cybersecurity and cyberforensics. This last column is the inspiration for this presentation at a Dagstuhl seminar with the title: Digital Evidence and Forensic Readiness. And the underlying and fundamental question (in the literal sense of the temple metaphor) is: Which processes can be automated – and which do we reserve for human (inter)action? The identification of these challenges gave birth to the idea of a new cross-disciplinary approach and the creation of its name – the "LEXONOMICS"-perspective[15].

Second: LEXONOMICS. "LEXONOMICS" is the research motto and desired outcome of the future efforts of the Faculty of Law and Economics at the Technical University of Darmstadt, Germany (there the research formation on Governance, Compliance and Regulation with its speaker Prof. Dr. Dirk Schiereck). LEXONOMICS is a compound of the Latin "LEX" with the Anglo-Saxon "ECONOMICS". Latin "LEX" also stands for the root of law in the history of law, and the Anglo-Saxon "ECONOMICS" refers to the interrelation of the legal and economic sciences in the future. From the "LEXONOMICS" perspective, the balancing test between "necessary effort" with "desired effect of protection" can be applied with new methods and insights. A first approach is § 9 BDSG[16] – the "Magna Carta" of IT security law in Germany – which has undergone firm establishment through new case law. A follow-up after the seminar exemplifies the potential and challenges for this "temple perspective" as well as "LEXONOMICS" regarding the second column:

Third: Follow-up of the seminar with the decision of the European Court of Justice from 8. April 2014. The second column of the temple architecture titled "Data retention without purpose limitation" was at dispute in the judgment of the *European Court (Grand Chamber), 8. April 2014, C-293/12 and C-594/12.* The court rendered the following decision:

> "Directive 2006/24/EC of the European Parliament and of the Council of 15 March 2006 on the retention of data generated or processed in connection with the provision of publicly available electronic communications services or of public communications networks and amending Directive 2002/58/EC is invalid."[17]

A core area of (European Union) Cyberlaw, the law allocating chances and risks, rights and obligations in cyberspace, was "established" with this judgment. It is noteworthy that

[13] "Information on legal remedies available".
[14] V. Schmid, in: H. Sodan/J. Ziekow, § 55a marginal number 151 et seqq.
[15] V. Schmid, in: H. Sodan/J. Ziekow, § 173 marginal numbers 10 and 57.
[16] Federal Data Protection Act in the version promulgated on 14 January 2003 (Federal Law Gazette [Bundesgesetzblatt] Part I p. 66), as most recently amended by Article 1 of the Act of 14 August 2009 (Federal Law Gazette Part I p. 2814), in force from 1 September 2009. This Act serves to implement directive 95/46/EC of the European Parliament and of the Council of 24 October 1995 on the protec-tion of individuals with regard to the processing of personal data and on the free movement of such data (OJ EC no. L 281, p. 31 ff.); non authentic translations provided by the Language Service of the Federal Ministry of the Interior under http://www.gesetzeiminternet.de/englisch_bdsg/index.html.
[17] Judgment of the European Court (Grand Chamber), 8. April 2014, C-293/12 and C-594/12, marginal number 73.

all other member-states of the European Union (with the exception of Germany) might have acted unlawfully by implementing this European Directive.[18] The only member-state (still) not[19] implementing that Directive, the Federal Republic of Germany, even had to face an infringement proceeding[20] in 2012 (Art. 258 et seqq. Treaty on the Functioning of the European Union (TFEU)) instituted by the European Commission. This information sets up the importance of this judgment of the European Court of Justice in April 2014. Very rarely does the European Court of Justice declare European Union Law – here the *Directive 2006/24/EC of the European Parliament and of the Council of 15 March 2006 on the retention of data generated or processed in connection with the provision of publicly available electronic communications services or of public communications networks and amending Directive 2002/58/EC*[21] – invalid. It is noteworthy that two organs of European Union Law (Art. 13 paragraph 1 Treaty on European Union (TEU)) had fundamentally different opinions concerning the European Union Law on data retention: The European Commission sued the Federal Republic of Germany for not implementing the Directive (Art. 258, 260 TFEU) whereas the European Court of Justice decided that the directive in dispute was unlawful. Not only the European Union Law was affected – "data retention law" also divided lawmakers and courts in Germany.

Moreover, in matters of IT Security Law (**"ITS-Law"**, acronym by the author) the European Court of Justice is in some aspects in line with the judgment of the highest German court, the Federal Constitutional Court, from March 2010. The legal issue in this decision was not European law, but German law, implementing the European directive (§ 113a, b TKG[22]. This Act serves to transpose the following Directives: Directive 2002/21/EC of the European Parliament and of the Council of 7 March 2002 on a common regulatory framework for electronic communications networks and services (Framework Directive) (OJ L 108 page 33); Directive 2002/20/EC of the European Parliament and of the Council of 7 March 2002 on the authori-sation of electronic communications networks and services (Authorisation Directive) (OJ L 108 page 21); , § 100g StPO[23]). Perhaps – that is remarkable from the "LEXONOMICS"-perspective – both courts declared IT-Security of **inestimable value** for digit(al)ization. In April 2014, the challenge is to compare and evaluate both approaches – the here so called "German" and the here so called "European Union" approach to IT-Security-Law (**"ITS-Law"**). The German Approach: The "magna carta" in German data-protection and IT-Security-Law is traditionally § 9 sentence 1 BDSG and annex and § 9 sentence 2 BDSG. This provision is so relevant that it is presented here:[24]

[18] Further research is initiated

[19] In retrospect in 2014: The German Government and Parliament tried to implement the Directive. A groundbreaking decision of the German Federal Constitutional Court in 2010 declared this implementation as unconstitutional.

[20] Action brought on 11 July 2012 – European Commission v Federal Republic of Germany (Case C-329/12).

[21] Official Journal L 105, 13/04/2006, P. 0054–0063.

[22] Telecommunications Act (Telekommunikationsgesetz – TKG) in the version promulgated on 22 June 2004 (Federal Law Gazette Part I p. 1190), as most recently amended by Article 4 subsection (108) of the Act of 7 August 2013 (Federal Law Gazette Part I p. 3154)

[23] Code of Criminal Procedure (Strafprozessordnung – StPO) in the version promulgated on 7 April 1987 (Federal Law Gazette Part I p. 1074, 1319), as most recently amended by Article 5 subsection (4) of the Act of 10 October 2013 (Federal Law Gazette Part I p. 3799); non authentic translations provided by the Language Service of the Federal Ministry of the Interior under http://www.gesetze-im-internet.de/englisch_stpo/.

[24] Accentuation by the author.

§ 9 BDSG [Technical and organizational measures]

Public and private bodies which collect, process or use personal data on their own behalf or on behalf of others shall take the necessary technical and organizational measures to ensure the implementation of the provisions of this Act, especially the requirements listed in the Annex to this Act. **Measures shall be necessary only if the effort required is in reasonable proportion to the desired purpose of protection.**

Annex (to § 9 sentence 1)

Where personal data are processed or used in automated form, the internal organization of authorities or enterprises is to be such that it meets the specific requirements of data protection. In particular, measures suited to the type of personal data or categories of data to be protected shall be taken

1. to prevent unauthorized persons from gaining access to data processing systems for processing or using personal data (access control),
2. to prevent data processing systems from being used without authorization (access control),
3. to ensure that persons authorized to use a data processing system have access only to those data they are authorized to access, and that personal data cannot be read, copied, altered or removed without authorization during processing, use and after recording (access control),
4. to ensure that personal data cannot be read, copied, altered or removed without authorization during electronic transfer or transport or while being recorded onto data storage media, and that it is possible to ascertain and check which bodies are to be transferred personal data using data transmission facilities (disclosure control),
5. to ensure that it is possible after the fact to check and ascertain whether personal data have been entered into, altered or removed from data processing systems and if so, by whom (input control),
6. to ensure that personal data processed on behalf of others are processed strictly in compliance with the controller's instructions (job control),
7. to ensure that personal data are protected against accidental destruction or loss (availability control),
8. to ensure that data collected for different purposes can be processed separately.

Traditionally, § 9 sentence 2 BDSG established that the level of IT-Security is the result of a balancing test between effort ("Aufwand") and effect ("angestrebter Schutzzweck"). In 2010, the German Federal Constitutional Court insisted for **German Constitutional Law** on a **particularly high standard of IT-Security** for the collection, storage, transmission and usage (processing) of telecommunication traffic data ("besonders hoher Sicherheitsstandard")[25], see also Press release no. 37/2008 of 19 March 2008, http://www.

[25] BVerfG, Urteil vom 02.03.2010, Az 1 BvR 256/08, 1 BvR 263/08, 1 BvR 586/08, http://www.bverfg.de/entscheidungen/rs20100302_1bvr025608.html, see also Press release no. 11/2010 of 2 March 2010, http://www.bundesverfassungsgericht.de/pressemitteilungen/bvg10-011en.html; BVerfG, 1 BvR 256/08 vom 11.3.2008 (application for a temporary injunction in the matter of "data retention"), http://www.bverfg.de/entscheidungen/rs20080311_1bvr025608.html. BVerfG, Urteil vom 02.03.2010, Az 1 BvR 256/08, 1 BvR 263/08, 1 BvR 586/08:
Leitsatz 4:
"Hinsichtlich der Datensicherheit bedarf es Regelungen, die einen **besonders hohen Sicherheitsstandard** normenklar und verbindlich vorgeben. Es ist jedenfalls dem Grunde nach gesetzlich sicherzustellen, dass sich dieser an dem Entwicklungsstand der Fachdiskussion orientiert, neue Erkenntnisse und Einsichten fortlaufend aufnimmt und nicht unter dem Vorbehalt einer freien Abwägung mit allgemeinen

bundesverfassungsgericht.de/pressemitteilungen/bvg08-037en.html.

In April 2014, the European Court of Justice insisted for **European Union Law** (Directive 2006/24/EC) also on a **particularly high standard of IT-Security** for the collection, storage, transmitting and usage (processing) of telecommunication traffic-data. Furthermore, the European Court explicitly **rejected the notion of a balancing test** between effort and effect:

> Moreover, as far as concerns the rules relating to the security and protection of data retained by providers of publicly available electronic communications services or of public communications networks, it must be held that Directive 2006/24 **does not provide for sufficient safeguards**, as required by Article 8 of the Charter, **to ensure effective protection** of the data retained against the risk of abuse and against any unlawful access and use of that data. In the first place, Article 7 of Directive 2006/24 does not lay down rules which are specific and adapted to (i) the vast quantity of data whose retention is required by that directive, (ii) the sensitive nature of that data and (iii) the risk of unlawful access to that data, **rules which would serve, in particular, to govern the protection and security of the data in question in a clear and strict manner in order to ensure their full integrity and confidentiality**. Furthermore, a specific obligation on Member States to establish such rules has also not been laid down.
> Article 7 of Directive 2006/24, read in conjunction with Article 4(1) of Directive 2002/58 and the second subparagraph of Article 17(1) of Directive 95/46, does not ensure that a particularly high level of protection and security is applied by those providers by means of technical and organisational measures, **but permits those providers in particular to have regard to economic considerations when determining the level of security** which they apply, as regards the costs of implementing security measures. [...][26]

As a consequence, the legal standards for IT-Security concerning telecommunication traffic-data have to be analyzed and discussed in the near future. There is the German model (§ 9 sentence 1 and annex and sentence 2 BDSG) and the hitherto European model of the legislation (see below) with the balancing test of effort and effect ("erforderlicher Aufwand und angestrebter Schutzzweck") on one hand and new case law ("Rechtsprechung") of the German Federal Constitutional Court and the European Court of Justice on the other hand – both postulating a very high standard of IT Security. There might be different IT Security Law (**"ITS-Law"**) perceptions in legislation and in judiciary. As mentioned above, the balancing test in European (Union) Law is established with the following articles:[27]

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wirtschaftlichen Gesichtspunkten steht." (accentuation by the author).
Randnummer 222:
Angesichts des Umfangs und der potentiellen Aussagekraft der mit einer solchen Speicherung geschaffenen Datenbestände ist die Datensicherheit für die Verhältnismäßigkeit der angegriffenen Vorschriften von großer Bedeutung. Dieses gilt besonders, weil die Daten bei privaten Diensteanbietern gespeichert werden, die unter den Bedingungen von Wirtschaftlichkeit und Kostendruck handeln und dabei nur begrenzte Anreize zur Gewährleistung von Datensicherheit haben. Sie handeln grundsätzlich privatnützig und sind nicht durch spezifische Amtspflichten gebunden. Zugleich ist die Gefahr eines illegalen Zugriffs auf die Daten groß, denn angesichts ihrer vielseitigen Aussagekraft können diese für verschiedenste Akteure attraktiv sein. Geboten ist daher ein **besonders hoher Sicherheitsstandard**, der über das allgemein verfassungsrechtlich gebotene Maß für die Aufbewahrung von Daten der Telekommunikation hinausgeht. Solche Anforderungen der Datensicherheit gelten dabei sowohl für die Aufbewahrung der Daten als auch für deren Übermittlung; ebenso bedarf es effektiver Sicherungen zur Gewährleistung der Löschung der Daten." (accentuation by the author).

[26] Judgment of the European Court (Grand Chamber), 8. April 2014, C-293/12 and C-594/12, marginal numbers 66, 67.

[27] Accentuation by the author.

Article 7 DIRECTIVE 2006/24/EC[28]**[Data protection and data security]**
Without prejudice to the provisions adopted pursuant to Directive 95/46/EC and Directive 2002/58/EC, each Member State shall ensure that providers of publicly available electronic communications services or of a public communications network respect, as a minimum, the following data security principles with respect to data retained in accordance with this Directive:
(a) the retained data shall be of the same quality and subject to the same security and protection as those data on the network;
(b) the data shall be subject to appropriate technical and organisational measures to protect the data against accidental or unlawful destruction, accidental loss or alteration, or unauthorised or unlawful storage, processing, access or disclosure;
(c) the data shall be subject to appropriate technical and organisational measures to ensure that they can be accessed by specially authorised personnel only;
and
(d) the data, except those that have been accessed and preserved, shall be destroyed at the end of the period of retention.

Article 4(1) DIRECTIVE 2002/58/EC[29]**[Security]**
1. The provider of a publicly available electronic communications service must take**appropriate technical and organisational measures** to safeguard security of its services, if necessary in conjunction with the provider of the public communications network with respect to network security. Having regard to the state of the art and the cost of their implementation, these measures shall ensure **a level of security appropriate to the risk** presented.

Article 17(1) Directive 95/46/EC[30]**[Security of processing]**
1. Member States shall provide that the controller must implement appropriate technical and organizational measures to protect personal data against accidental or unlawful destruction or accidental loss, alteration, unauthorized disclosure or access, in particular where the processing involves the transmission of data over a network, and against all other unlawful forms of processing.
Having regard to the state of the art and the cost of their implementation, such measures shall ensure **a level of security appropriate to the risks** represented by the processing and the nature of the data to be protected.
These are prerogatives and prerequisites for digit(al)ization and therefore challenges that "LEXONOMICS" might master.

[28] Directive 2006/24/EC of the European Parliament and of the Council of 15 March 2006 on the retention of data generated or processed in connection with the provision of publicly available electronic communications services or of public communications networks and amending Directive 2002/58/EC, Official Journal L 105, 13/04/2006, P. 0054–0063.
[29] Directive 2002/58/EC of the European Parliament and of the Council of 12 July 2002 concerning the processing of personal data and the protection of privacy in the electronic communications sector (Directive on privacy and electronic communications), Official Journal L 201 , 31/07/2002 P. 0037 – 0047.
[30] Directive 95/46/EC of the European Parliament and of the Council of 24 October 1995 on the pro-tection of individuals with regard to the processing of personal data and on the free movement of such data, Official Journal L 281 , 23/11/1995 P. 0031–0050.

References

German literature and references about "Informatisierung" (as at February 2014) can be found in *Schmid*, V., in: H. Sodan/J. Ziekow, Großkommentar zur Verwaltungsgerichtsordnung, 4th Edition 2014, §§ 55a and b (soon to be published).
The provided literature is German-language and not Anglo-Saxon. Nevertheless, three very renowned authors are recommended here (in alphabetic order):

- *Berlit, U.*, Elektronischer Rechtsverkehr – eine Herausforderung für die Justiz, JurPC Web-Dok. 173/2013, Abs. 1–50;
- *Herberger, M.*, Zehn Anmerkungen zum "Gesetz zur Förderung des elektronischen Rechtsverkehrs mit den Gerichten", JurPC Web-Dok. 81/2013, Abs. 1–66;
- *Köbler, R.*, Der elektronische Rechtsverkehr kommt; Fahrplan bis 2022 steht, AnwBl 2013, 589.

3.14 ICT Policy in Norwegian Industries

Rhythm Suren Wadhwa (Gjøvik University College, NO)

This abstract discusses ICT policy in the Norwegian industrial context. Norway was able to move from an agro-based economy to an industrial one within a single generation. The public sector acted both as a facilitator and a pace-setter with the private sector driving the economic development. Since ICT accelerates information & knowledge development and consumption, ICT, by default, was seen as the key driver of future growth in all phases of work & life. In national development, ICT can be said to play a dual role; one, as a production sector to achieve development goals and value creation; and two as an enabler in moving towards knowledge society and knowledge economy. A migration strategy towards attaining the objective of attaining competitiveness and equity were identified to provide overall guidance for the development: ICT as a sector and information as a commodity; value creating knowledge products and services; and competitive knowledge economy. Two major initiatives to address issues of economic competitiveness and social equity were in taking ICT development as a sector and as an enabler. The policy framework delineates strategic, tactical and operational aspects of policy intervention. Some of the lessons learnt are that visionary leadership and championship are necessary to provide vision and motivation, and to see projects to the end; academia-industry partnership and innovation clusters are a must to move fast and a planned approach is a must. A top-down strategic intervention becomes imperative to attain a benchmark position.

4 Working Groups

4.1 Digital forensic readiness processes and procedures for investigators

Hein Venter (University of Pretoria, ZA)

Well-documented processes are required for digital forensic readiness. Such processes can help to define detailed procedures that can be used in the rest of the digital forensic investigation process as portrayed in ISO27043. Following is a non-exhaustive list of typical processes that can be included for digital forensic readiness:

- Creation of audit logs
- Retention of audit logs
- Processing of logs
- Presentation of the logs
- Correlation of logs
- Transmission of logs
- Validation of logs

For example, consider the following scenario. Suppose a bank implements the processes as discussed above. Further, suppose that it is alleged that an employee of the bank leaked confidential information to a competitor bank via email.

Assume that the bank had policies in place to implement the processes as defined above. For example, the email server of the bank retains all emails sent. The firewall logs all incoming and outgoing network traffic and logs that an email with an attachment was sent to an unusual email address – that of the competitor bank. Some log correlation between the email and firewall servers' logs are automatically done by a log correlation system. A flag is raised by the intrusion detection system of the bank, warranting for a potential investigation to follow.

With the digital forensic readiness processes in place, the above was possible. Assume that there is now an enquiry launched into the allegations. However, without the above information, a digital forensic investigator will have to follow the normal digital forensic investigation process as stated in ISO27043. This entails the following processes to be followed:

- Prepare for the investigation (e.g. obtain authorization, such as to obtain a search warrant)
- Seize the employee's PC
- Acquire the hard drive from the PC
- Analyze the data for potential evidence and continue with the rest of the processes described in ISO27043

Remember that the above processes have been followed as if there were no digital forensic readiness processes in place. Should these processes be in place, however, the investigator need not follow all of the processes in ISO27043 as described above. This is so because the evidence required would have already been logged and the investigator need only to get authorization after which he can already start with the analysis of the data already available in log correlation system. The obvious advantage is that much time and cost is saved in this situation. What is more, the investigator have access to several other logs created by the digital forensic readiness system. Detailed procedures should then be defined in order to enhance each of the digital forensic investigation processes found in ISO27043. For example,

now that more log data is available, detailed procedures can be defined on how to access the particular logs in order to identify even more compelling evidence.

4.2 Notion of Digital Evidence

Isabel Taylor (Universiät Tübingen, DE)

4.2.1 Authorship

The editor of this abstract would like to thank Nigel Wilson, Carsten Momsen, Raymond Choo, Stefanie Gerdes, Rhythm Suren Wadhwa, Christian Moch, Lee Tobin and Nils-Peter Hercher, as well as the members of the Definitions and Concepts Working Group – Viola Schmid, Thomas Kemmerich, Barbara Endicott-Popovsky, Aaron Alva, and Günther Diederich – for their valuable contributions and insights during the writing of this section.

4.2.2 The definitional problem

Terminology determines the way we perceive the world. We cannot engage in a meaningful discourse if we cannot agree on the definitions of terms. The concept of definition is the filter through which our understanding of solutions and outcomes is defined, but definitions are inevitably contextual, language-based and fluid. Glossaries are an important means of collating consistent terminology, but there are often difficulties with over-definition, particularly by non- subject specialists and in non-dynamic environments. The same terms may be defined in subtly different ways across different disciplines, which can lead to confusion in interdisciplinary discussions. The differences between the definitions may in some cases be profound, such as (for example) the definition of 'data' in ICT versus its definition in the 1995 Data Protection Directive. However, we acknowledge the important glossary projects that are ongoing outside the scope of this project.

4.2.3 Legal terminology

The current definitions in the literature are specific to a local area, and this is acutely so in law, because it is procedural and jurisdiction based. For example, 'privacy', which is highly relevant in the German environment – in terms of admissibility and forensics – has different legal impacts in different jurisdictions, and differing definitions.

Evidence provides a particularly good example of different categorisations having different legal effects and outcomes. These categorisations have both substantive and procedural (adjectival) implications. Depending on the jurisdiction, the categories of evidence are defined differently and the breadth and significance of the categories also varies. For example, the common law system makes a conceptual distinction between real (traditionally, physical) evidence and documentary evidence. Digital evidence bridges both categories. By contrast, categories of evidence have less impact on admissibility in the German system, where digital records often fall into the Augenscheinsbeweis ("visual inspection") category, such as a USB stick, or Urkundenbeweis (documentary evidence), i.e. the documents on the USB stick.

Additionally, 'soft law' such as the ISO standards influences the manner in which terms are understood, both within the regulatory environment and in practice. For example,'information assurance' has been defined by ISO 27001.

4.2.4 ICT

Information and Communication Technologies (ICT) presents its own particular set of challenges: indeed, the foundation of ICT is "language-based." Coupled with this is the fast pace of technological change. The terminology needs to be updated constantly, since new terms and buzzwords are always emerging: for example, "big data," or the "Internet of things." Sometimes there is a lack of consensus on the meanings of terms, such as "digital". File location has a particular meaning in the ICT forensic context, and some expressions, like "hash," or "byte," only have meaning in this particular discipline, and require 'translation' to be understood by those in other disciplines. The magnitude and dimension of ICT terms pose a particular conceptual challenge for those outside the area: for example, the conception of a terabyte of information, often requiring explanation by means of (often unsatisfactory) analogy to lay audiences. This has particular relevance when regulations or standards are developed that impact the ICT field: a common problem is the lack of understanding, on the part of legal specialists, of ICT-specific terms.

4.2.5 Archival terms

Since archival science is concerned with the preservation of documents that can be shown to be authentic, reliable and accurate– a function which derives from its roots in the legal world– its concepts and terminology are helpful to discussions of digital evidence. In particular, archival theory provides a set of conceptual parameters which assist in identifying "records" within the digital environment, and a definition of "trustworthiness" (the authenticity, reliability and accuracy of a document) which can help to inform the assessment of digital evidence. Archival science shares terms with both the legal and ICT fields. For example, the archival idea of the chain of custody has an analogue in the similar legal concept, often applied to police exhibits, while ICT and archival science both share an emphasis on metadata. Archival science provides essential concepts which can inform system requirements for the preservation of records' evidential value: classical concepts such as provenance (the history of the custody of the records and the way this has changed over time) and respect des fonds (the management of records based on creator) continue to inform digital archivists and are clearly relevant to the new digital environment.

4.2.6 Research projects

The interdisciplinary work in this and other working groups was accompanied by a constant discussion on definitions, concepts and notions in digital evidence and forensic readiness. In addition to this working group, a dedicated working group on "Definitions and Concepts" aimed at defining the gap between the different areas of expertise. A summary of their intermediate results has been integrated into this report in order to present a whole view on notions, definitions and concepts.

In discussions concerning seemingly well-defined terms, the need for a unified glossary soon became evident. In order to start on this extensive task, the working group on "Definition and concepts" developed a methodology for input on glossary terms. First, they focused on collecting terms. Second, they differentiated between "clear" and "hard" cases for the terms collected. Third, they determined to do research in legal and technological sources. Fourth, they decided to refer to the "Origins of Evidence" group for a discussion of terms' history: adopting this coordination and cooperation strategy, they exchanged ideas with break-up teams on alternative perspectives and methods. Fifth, they proposed to start a matrix of legal sources, initially focusing on European Law, German Law, and Common

Law. Sixth, they pointed out that the methodology provides non-exhaustive research as a starting-point, but the community's input is needed to add depth and perspective from each area of expertise involved in forensic readiness.

With the differing area-specific definitions revealed in the discussion of the "Definitions and Concepts" working group, the need for a unified Glossary soon became evident. Therefore the "Notion of Digital Evidence" group recommends a commitment to definitively establishing the definition and parameters of the term "forensic readiness" and to this end:

- the development of a multi-regional glossary, including ICT, law and archives, to enable the identification of definitions relating to digital evidence that work across the disciplines and jurisdictions
- a multi-lingual collection of precedents that define relevant terminology, particularly those that sum up the state of the art, with a commentary in English.

4.2.7 Strategies

Increase consultation between the different disciplines and internationally. Begin an open dialogue between ICT and policy-makers, relevant industry, and government administration, so that policy-makers are informed of emerging technological challenges to the existing law. Develop catalogues of criteria for the creation, preservation and use of digital evidence, to increase certainty about the state of forensic readiness in a given situation.

4.3 Forensic readiness landscape

Hein Venter (University of Pretoria, ZA)

Joint work of Valjarevic, Aleksandar; Venter, Hein S.; Forte, Dario

There are, at the time of writing this paper, many standardization initiatives happening within many standardization bodies with regards to standardization of the digital forensic investigation process. Perhaps one of the most comprehensive standardization efforts currently happens within ISO. ISO27043 is the so-called umbrella standard, covering the width of the entire digital forensic investigation process.

ISO27043 provides guidelines that encapsulate idealized models for common digital forensic investigation processes across various investigation scenarios. This includes processes from digital forensic readiness up to and including investigation closure. A basic principle of digital forensic investigations is repeatability, where a suitably-skilled investigator should be able to obtain the same result as another similarly-skilled investigator, working under similar conditions. This principle is exceptionally important to any general investigation. Guidelines for many investigation processes have been provided in the standard in order to ensure that there is clarity and transparency in obtaining the produced result for each particular process.

Established guidelines covering digital forensic investigation principles and processes would expedite investigations, because they would provide a common order of the events that an investigation entails. Using established guidelines allows smooth transition from one event to another during an investigation. Such guidelines would also allow proper training of inexperienced investigators. The guidelines, furthermore, aim to ensure flexibility within an investigation due to the fact that many different types of digital investigations are possible, such as computer forensics (investigations on PCs), mobile phone (smart device) forensics,

network forensics, cloud forensics (a kind of network forensics), and live forensics (i.e. volatile memory forensics).

By the time of writing, ISO27043 was still in a draft, yet nearly finalized, state. The need within the digital forensic investigation community is widely acknowledged for the establishment of a harmonized digital forensic investigation process model, however, both in a criminal prosecution setting and in other environments, such as corporate breaches of information security. Such harmonized incident investigation principles and processes are specified within the standard and indications are provided of how the investigation processes can be customized in different investigation scenarios.

The provided guidelines give succinct guidance on the exact process to be followed during any kind of digital forensic investigation in such a way that, if challenged, no doubt should exist as to the correctness of the investigation process followed during such an investigation.

Any digital investigation requires a high level of expertise. Those involved in the investigation should be competent, proficient in the processes used, and they should use processes which are compatible with the relevant policies and/or laws in various jurisdictions across the world.

Where the need arises to assign a process to a person, that person will take the responsibility for the process. Therefore, a strong correlation between a process responsibility and a person's input will determine the exact investigation process required according to the harmonized investigation processes provided as guidelines in ISO27043.

ISO27043 is intended to complement other standards and documents which give guidance on the investigation of, and preparation to investigate, information security incidents. It is not a comprehensive guide, but lays down certain fundamental principles which are intended to ensure that tools, techniques and methods can be selected appropriately and shown to be fit for purpose should the need arise. The standard also intends to inform decision-makers that need to determine the reliability of digital evidence presented to them. It is applicable to organizations needing to protect, analyze and present potential digital evidence. It is relevant to policy-making bodies that create and evaluate procedures relating to digital evidence, often as part of a larger body of evidence.

ISO27043 describes part of a comprehensive investigative process which includes, but is not limited to, the application of the following related standards. Note that, at the time of writing, all parts of this standard were in development, except for ISO27037, which was published in 2012.

- ISO27035: Information security incident management. This is a three part standard that provides organizations with a structured and planned approach to the management of security incidents. It is composed of three parts:
  - Part 1: Principles of incident management.
  - Part 2: Guidelines to plan and prepare for incident response.
  - Part 3: Guidelines for incident response operations.
- ISO27037: Guidelines for the identification, collection, acquisition and preservation of digital evidence.
- ISO27038: Specification for digital redaction.
- ISO27040: Storage security.
- ISO27041: Guidance on assuring the suitability and adequacy of incident investigation methods.
- ISO27042: Guidelines for the analysis and interpretation of digital evidence.
- ISO27044: Guidelines for Security Information and Event Management (SIEM).
- ISO27050: Electronic discovery.
- ISO30121: Governance of digital forensic risk framework.

The digital investigation processes of ISO27043 are multi-tiered, where each process would contain a set of sub-processes. Sub-processes can only be fully defined for a specific type of incident and investigation. Legal rules will also likely have a high impact on the definition of sub-processes. Digital investigation processes can be categorized into the following digital investigation process classes:

- readiness processes: That class of processes dealing with pre-incident investigation processes. This class deals with defining strategies which can be employed to ensure systems are in place, and that the staff involved in the investigative process are proficiently trained prior to dealing with an incident occurring. The readiness processes are optional to the rest of the digital investigation processes. Readiness processes include the following:
- planning and definition of system architectures for establishing digital forensic readiness;
- implementing digital forensic readiness system architecture;
- assessment of implementation;
- initialization processes: That class of processes dealing with the initial commencement of the digital investigation. Initialization processes include the following:
- incident detection;
- first response;
- planning;
- preparation.
- acquisitive processes: That class of processes dealing with the physical investigation of a case where potential digital evidence is identified and handled. Acquisitive processes include the following:
- potential digital evidence identification;
- potential digital evidence acquisition;
- potential digital evidence transportation;
- potential digital evidence storage.
- investigative processes: That class of processes dealing with uncovering the potential digital evidence. Investigative processes include the following:
- potential digital evidence examination and analysis;
- digital evidence interpretation;
- reporting;
- presentation;
- investigation closure.
- concurrent processes: That class of processes that continues concurrently alongside the other processes. This class of processes differ from the previous classes in the sense that they happen in tandem with the other processes instead of linear. In addition, the particular order in which the concurrent processes execute is irrelevant as opposed to the other non-concurrent processes. Concurrent processes include the following:
- obtaining authorization;
- documentation;
- managing information flow;
- preserving chain of custody;
- preserving digital evidence;
- interaction with the physical investigation.

The six concurrent processes are aimed at allowing the said processes to be executed as on-going processes. The reason for having the concurrent processes is mainly to ensure more effective admissibility of digital evidence into a legal system, since, in the case of not having such processes, any investigation may run the risk that the admitted potential evidence

might not be suitable for litigation due to improper handling and documentation of potential digital evidence. These concurrent processes are, thus, based on principles that need to be followed throughout a digital investigation, alongside with the other classes of processes.

References

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4.4 Forensic readiness: evidence in the digital world

Joe Cannataci (University of Malta, MT)

4.4.1 Landscape: the legal landscape for the treatment of evidence – Joe Cannataci

Evidence can take many forms: it may be a bullet or a blood-stained shirt or some such tangible three-dimensional object which is not digital but which may also be captured digitally whether through a two or 3D image or through a document which describes the artefact. It may be one or more documents which were created in a written or printed form most often on paper and which are also capable of being captured digitally in facsimile. It may also take the form of correspondence or publications or records of transactions which were "born digital" such as a word-processed document or e-mail or other user-generated content in an on-line environment or indeed digital photographs. Many "born digital" records would also largely consist of transactional data or traffic data such as telephone records or credit card records or electricity bills. Almost by definition most items which end up as evidence whether digital or non-digital were not intended to be used as evidence when they were created. Their use as evidence is secondary to their primary purpose, to their real "raison d'etre". Whether non-digital or digital evidence, the role of a bullet or a paper document or an e-mail as evidence is one which comes in at a later stage, when the artefact or record could help prove that an allegation about human behavior is true or false. In this sense historically there was no such thing as forensic readiness. Forensic sciences were developed to obtain information from artefacts and records which were most often never designed ab initio to in any way assist the forensic process in a court of law. Indeed an artefact or a record enters into the forensic process only if an incident, (criminal, civil or commercial) forces it to do so. Otherwise, for all of its natural lifespan the artefact or record will remain outside the forensic process and thus forensically irrelevant – though it may continue to be very relevant to its user or owner. The introduction of ICTs into the "forensic food chain" over the past forty years or so (much less in some countries) have led to more and more evidence being stored, transmitted and managed in a digital manner. It should be borne in mind that evidence is not only collected, processed and stored in those stages before a case is hear in court. More and more evidence is generated in the course of most court hearings with witnesses being recorded and their testimony entered into the official court record, irrespective of whether a case is criminal or civil. In a properly-organised e-justice or e-court system – indeed in most manual systems too – each new piece of testimony or evidence is allocated a new unique identifier which accompanies it and stays with it for the duration of the court proceedings and normally after these are completed too.

The ICT systems used by courts of law, administrative tribunals, land registries, public registries, public prosecutors, private law firms and solo law practitioners have grown organically over the years since they first started appearing in the 1970s. More often than not legal information retrieval systems and case management systems were not designed and developed according to some regional, national or international master-plan. Instead, most often, they grew higgledy-piggledy depending on the initiative, resources and resourcefulness of the actors in the local legal scene. Some courts and law firms in some countries computerized at a much faster rate than others in the same country or outside that country. Some forty years after "legal informatics" appeared on the scene in Europe the results and levels of computerization in different countries varies considerably. The disparity in the capability of different systems creates significant obstacles to the portability of evidence across different jurisdictions within and outside Europe thus contributing to delays and increase in costs of legal proceedings. This has led to a perceived need in the European Union context to have a Common Framework regulating the implementation of ICTs in the use, collection and exchange of evidence in criminal trials. However, legislation on criminal procedures in many European countries were enacted before these technologies appeared, thus taking no account of them and creating a scenario where criteria are different and uncertain, regulations are not harmonised and aligned and therefore exchange among EU countries jurisdictions, at transnational level, is very hard to be achieve in practice. What is also missing is a Common European Framework to guide policy makers, Law Enforcement Agencies (LEAs), judges/magistrates as well as lawyers and prosecutors when dealing with digital evidence treatment and exchange. From a European perspective this situation has led to the European Commission in 2014 making some limited funds available for the preliminary steps to be taken to create an evidence base and a roadmap for policy makers to attempt to find means to resolving the problems intrinsic to the fragmentation which characterizes legal informatics across the court systems in 28 EU member states. The EVIDENCE project sets out to plug part of the gap that is the missing common legal layer devoted to the regulation of electronic evidence in courts. A common guide identifying the value to be assigned to electronic evidence all over EU Member states, common criteria for reliability of electronic evidence independently from the country or LEA by which is gathered, reliability, validity and integrity of the electronic proof, and so forth. It also seeks to investigate the common background for all policy makers that must regulate the use of electronic evidence in their national scenario, for LEAs and other major actors in gathering electronic evidence, for judges, magistrates evaluating such electronic evidence in trials, for prosecutors and for lawyers, using electronic evidence for conducting someone's defence. Given the limited funding available, the EVIDENCE Project restricts itself to a number of basic initial steps: first of all at developing a road map (guidelines, recommendations, technical standards, research agenda) aimed at creating a Common European Framework for the systematic, aligned and uniform application of new technologies in the collection, use and exchange of evidence. By defining the Road map it will also discuss the treatment of evidence gathered by using new technologies, the specific rules and criteria for treatment of both digitized and born-digital evidence, what are the implications for privacy and ethical issues and finally, which are the conditions for a secure and consistent exchanging of evidence collected by means of new technologies. In the United States The Sedona Conference®, claims to be the pre-eminent thought leader in eDiscovery, and is in spring 2014 organising a regional program on Cross-Border Discovery and Data Protection Laws. The conference is being held in conjunction with Sedona's Working Group 6 on International Electronic Information Management, Discovery and Disclosure. Despite the International in the name it appears fair

to say that Sedona remains a very US-centric affair with limited international impact. On the other hand it is reported that within the United States the guidelines published by Sedona in this field are widely respected and followed. The interdisciplinary specialists meeting within Dagstuhl Seminar 14092 together created the illustration of the iter of various categories of non-digital and digital evidence through the forensic process as illustrated in Fig 0. Onto this flow-chart they then mapped on existing efforts at introducing digital forensics standards such as ISO/IEC 27037, 27041, 27042 and 27043 in particular which are in the process of being created to promote good practice forensic investigation involving digital evidence. The extent to which the proposed new standard 27043 fitted legal realities is described in the section on ISO 27043 below. The quality of digital records was then also discussed from the perspective of archival sciences. In summary it was agreed that archival sciences may contribute to the treatment of digital and non-digital evidence in three main ways:

1. By optimizing the design of new corporate or public IT systems at the record-creation, management and preservation stages
2. By optimizing new e-court or e-justice systems and help them move to "ideal record form"
3. By maximising the utility of diplomatics – archival diplomatics may be useful in analysis in a retrospective way esp for existing records which were not designed to ideal record form.

The way that archival sciences may contribute to the process is described in more detail in the relative section below. Finally, the working group also discussed the current status quo from the perspective of It security professionals which is also briefly outlined in the relative section below.

4.4.2 Standardisation efforts and ISO – Hein S. Venter

There are, at the time of writing this paper, many standardization initiatives happening within many standardization bodies with regards to standardization of the digital forensic investigation process. Perhaps one of the most comprehensive standardization efforts currently happens within ISO. ISO27043 is the so-called umbrella standard, covering the width of the entire digital forensic investigation process. ISO27043 provides guidelines that encapsulate idealized models for common digital forensic investigation processes across various investigation scenarios. This includes processes from digital forensic readiness up to and including investigation closure. A basic principle of digital forensic investigations is repeatability, where a suitably-skilled investigator should be able to obtain the same result as another similarly-skilled investigator, working under similar conditions. This principle is exceptionally important to any general investigation. Guidelines for many investigation processes have been provided in the standard in order to ensure that there is clarity and transparency in obtaining the produced result for each particular process. Established guidelines covering digital forensic investigation principles and processes would expedite investigations, because they would provide a common order of the events that an investigation entails. Using established guidelines allows smooth transition from one event to another during an investigation. Such guidelines would also allow proper training of inexperienced investigators. The guidelines, furthermore, aim to ensure flexibility within an investigation due to the fact that many different types of digital investigations are possible, such as computer forensics (investigations on PCs), mobile phone (smart device) forensics, network forensics, cloud forensics (a kind of network forensics), and live forensics (i.e. volatile memory forensics). By the time of writing, ISO27043 was still in a draft, yet nearly finalized, state. The need within the digital forensic investigation community is widely acknowledged for the establishment of a harmonized digital forensic investigation process model, however, both in a criminal prosecution

setting and in other environments, such as corporate breaches of information security. Such harmonized incident investigation principles and processes are specified within the standard and indications are provided of how the investigation processes can be customized in different investigation scenarios.

The provided guidelines give succinct guidance on the exact process to be followed during any kind of digital forensic investigation in such a way that, if challenged, no doubt should exist as to the correctness of the investigation process followed during such an investigation.

Any digital investigation requires a high level of expertise. Those involved in the investigation should be competent, proficient in the processes used, and they should use processes which are compatible with the relevant policies and/or laws in various jurisdictions across the world. Where the need arises to assign a process to a person, that person will take the responsibility for the process. Therefore, a strong correlation between a process responsibility and a person's input will determine the exact investigation process required according to the harmonized investigation processes provided as guidelines in ISO27043. ISO27043 is intended to complement other standards and documents which give guidance on the investigation of, and preparation to investigate, information security incidents. It is not a comprehensive guide, but lays down certain fundamental principles which are intended to ensure that tools, techniques and methods can be selected appropriately and shown to be fit for purpose should the need arise. The standard also intends to inform decision-makers that need to determine the reliability of digital evidence presented to them. It is applicable to organizations needing to protect, analyze and present potential digital evidence. It is relevant to policy-making bodies that create and evaluate procedures relating to digital evidence, often as part of a larger body of evidence. ISO27043 describes part of a comprehensive investigative process which includes, but is not limited to, the application of the following related standards. Note that, at the time of writing, all parts of this standard were in development, except for ISO27037, which was published in 2012.

- ISO27035: Information security incident management. This is a three part standard that provides organizations with a structured and planned approach to the management of security incidents. It is composed of three parts:
  - Part 1: Principles of incident management.
  - Part 2: Guidelines to plan and prepare for incident response.
  - Part 3: Guidelines for incident response operations.
- ISO27037: Guidelines for the identification, collection, acquisition and preservation of digital evidence.
- ISO27038: Specification for digital redaction.
- ISO27040: Storage security.
- ISO27041: Guidance on assuring the suitability and adequacy of incident investigation methods.
- ISO27042: Guidelines for the analysis and interpretation of digital evidence.
- ISO27044: Guidelines for Security Information and Event Management (SIEM).
- ISO27050: Electronic discovery.
- ISO30121: Governance of digital forensic risk framework.

Figure 2 shows typical activities surrounding an incident and its investigation. The numbers shown on this diagram (e.g. 27037) indicate the respective international standards listed above, and the shaded bars show where each is most likely to be directly applicable or has some influence over the investigative process (e.g. by setting policy or creating constraints). It is recommended, however, that all should be consulted prior to, and during, the planning and preparation phases. The process classes shown are defined fully in ISO27043

and the activities identified match those discussed in more detail in ISO27035, ISO27037, and ISO27042.

The digital investigation processes of ISO27043 are multi-tiered, where each process would contain a set of sub-processes. Sub-processes can only be fully defined for a specific type of incident and investigation. Legal rules will also likely have a high impact on the definition of sub-processes. Digital investigation processes can be categorized into the following digital investigation process classes:

- readiness processes: That class of processes dealing with pre-incident investigation processes. This class deals with defining strategies which can be employed to ensure systems are in place, and that the staff involved in the investigative process are proficiently trained prior to dealing with an incident occurring. The readiness processes are optional to the rest of the digital investigation processes. Readiness processes include the following:
- planning and definition of system architectures for establishing digital forensic readiness;
- implementing digital forensic readiness system architecture;
- assessment of implementation;
- initialization processes: That class of processes dealing with the initial commencement of the digital investigation. Initialization processes include the following:
- incident detection;
- first response;
- planning;
- preparation.
- acquisitive processes: That class of processes dealing with the physical investigation of a case where potential digital evidence is identified and handled. Acquisitive processes include the following:
- potential digital evidence identification;
- potential digital evidence acquisition;
- potential digital evidence transportation;
- potential digital evidence storage.
- investigative processes: That class of processes dealing with uncovering the potential digital evidence. Investigative processes include the following:
- potential digital evidence examination and analysis;
- digital evidence interpretation;
- reporting;
- presentation;
- investigation closure.
- concurrent processes: That class of processes that continues concurrently alongside the other processes. This class of processes differ from the previous classes in the sense that they happen in tandem with the other processes instead of linear. In addition, the particular order in which the concurrent processes execute is irrelevant as opposed to the other non-concurrent processes. Concurrent processes include the following:
- obtaining authorization;
- documentation;
- managing information flow;
- preserving chain of custody;
- preserving digital evidence;
- interaction with the physical investigation.

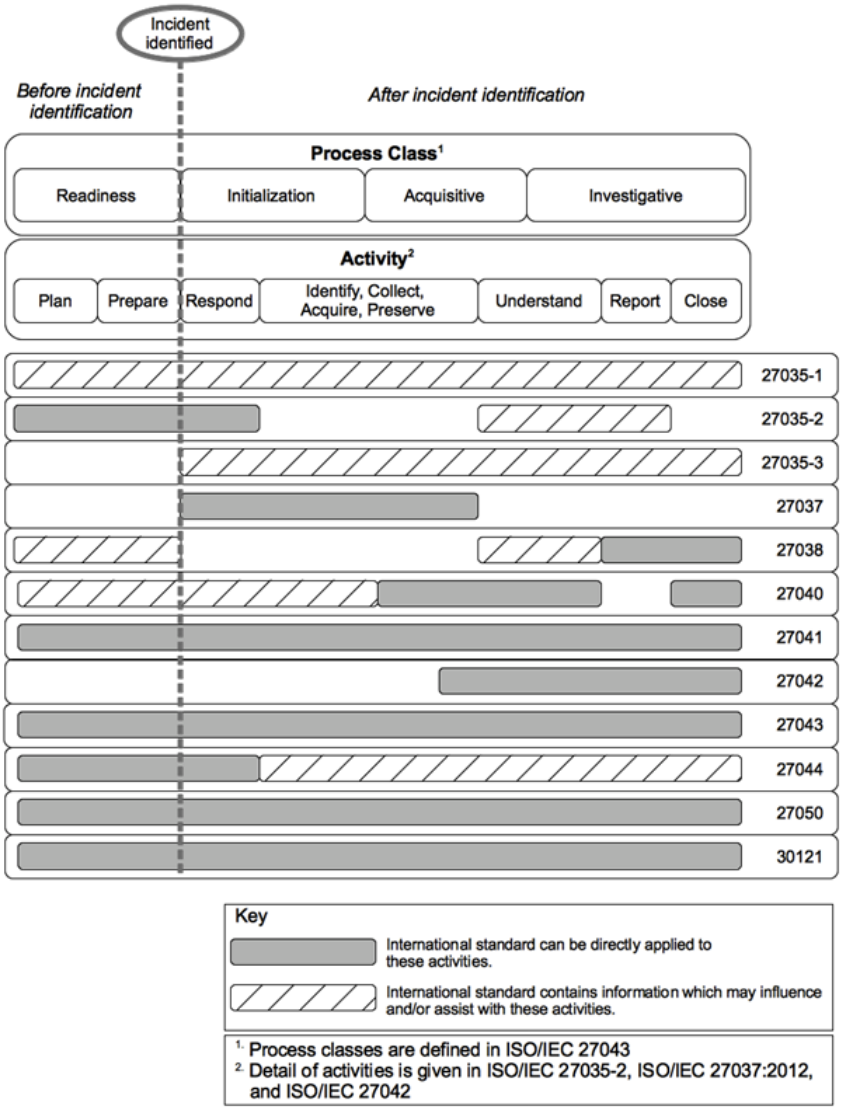


Figure 2 Applicability of standards to investigation process classes and activities.

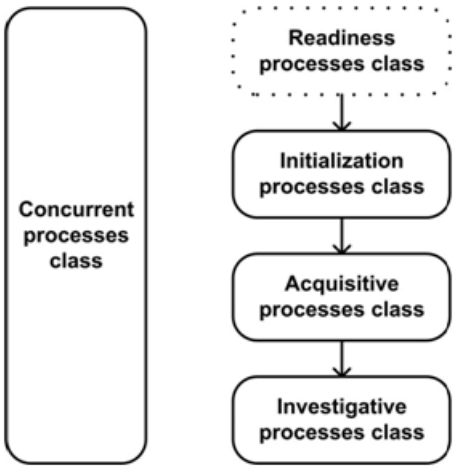


Figure 3 The various classes of digital forensic investigation processes in ISO27043.

Figure 3 shows the relationships between the various classes of digital investigation processes. Note that the dotted lines around processes in all figures indicate that the particular process is optional.

The six concurrent processes are aimed at allowing the said processes to be executed as on-going processes. The reason for having the concurrent processes is mainly to ensure more effective admissibility of digital evidence into a legal system, since, in the case of not having such processes, any investigation may run the risk that the admitted potential evidence might not be suitable for litigation due to improper handling and documentation of potential digital evidence. These concurrent processes are, thus, based on principles that need to be followed throughout a digital investigation, alongside with the other classes of processes.

4.4.3 The contribution of the archival sciences – Corinne Rogers

The ease with which digital material can be altered, intentionally or accidentally, and the ease with which it can be disseminated, shared, combined, and repurposed, has driven security, privacy, and rights concerns across domains and disciplines. Two of the most challenging issues presented by digital technology to the law enforcement, records management, archival and legal professions, researchers, business, government and the public are the identification of "records" in digital systems, and the determination of their "authenticity" [2]. These issues may be addressed from the archival perspective, backed by archival theory and methodology, and specifically by digital diplomatics. They are also addressed from a technological perspective, by the methods and tools of digital forensics. At the most basic level, both digital archivists and digital forensics practitioners are concerned with discovering, understanding, describing and presenting information inscribed on digital media.

Shared theoretical perspectives of digital forensics and digital archival practice include: (1) authorship and identity (authenticity of origin and forgery), (2) informational pattern and change over time (reconstruction and relationships among extant traces and objects), (3) evidential reliability (provenance and integrity), and (4) digital materiality and ornament (contextual detail and interpretation). There are also common pressing challenges in finding, processing and sustaining digital information: (1) the volume of a person's life information spread across myriad devices, along with the exacerbating complexity of diverse applications and locations – local machines and media, network servers and remote cloud services; (2) the

necessary versatility of tools, techniques and models required to capture and investigate digital information and to marshall metadata and description; (3) the forward looking process and activity required to ensure sustainability and long term digital preservation; and (4) the intensifying role of information assurance, data security planning, and protection of privacy and other digital rights [8].

The core archival functions are identified as appraisal and acquisition, arrangement and description, retention and preservation, management and administration, and reference and access. Furthermore, research may be considered the foundation of each archival activity [3]. Archival research has focused historically on records, defined as documents made or received in the course of practical activity, and set aside for further action or reference [4], as the primary objects of investigation. Archivists are concerned with establishing the evidentiary capacity of documents, and analyzing their evidential value, whether they are preserved primarily as records (as with a public organisation) or for their informational value as personal memory or legacy (as with a personal archive).

The science of diplomatics originated in the 17th century to establish the authenticity, and indirectly, the reliability, of archival documents, in order to determine rights and to identify and eliminate forgeries. It studies the genesis, forms, and transmission of records, the relationships of the records with associated actions, persons, and legal consequences [1]. Digital diplomatics has developed to provide a framework for assessing the authenticity of digital records and offers a powerful methodology for analyzing digital records. However, digital diplomatics alone may not be sufficient to understand the challenges posed to information inscribed by increasingly complex digital systems [2].

The lifecycle of authentic digital records, from the development of records systems through generation, maintenance, use, and preservation of records is captured in the Chain of Preservation (COP) model (Consultation draft – [5]). This model, developed through the research of the InterPARES Project (http://www.interpares.org), reflects archival theory and archival diplomatics, and complies with the requirements of the Open Archival Information System (OAIS) Reference Model, ISO 14721:2003 Space data and information transfer systems (see appendix for and example of key diagrams). The model identifies all the activities and actions that must be undertaken to ensure that digital records are properly generated in the first instance, maintain their integrity over time, and can be reproduced at any time throughout their existence. As well, it characterizes the metadata that must be gathered, stored and utilized throughout the lifecycle. Preliminary work has been done in mapping elements of the COP model to a general digital forensics process model [7]. Such an integration is intended to assist in establishing requirements for digital evidence and forensic readiness.

4.4.4 Digital forensics in IT security incident management

4.4.4.1 Historical perspective

The application of digital forensic methods for the investigation of security incidents grew out of the use of computer forensics in criminal investigations. Starting in the mid-1990, many organisations developed internal security incident response capabilities and the investigation of security breaches was an important part. While initially focused on the collection and analysis of digital traces from individual computer hard drives, with computers becoming network-centric the monitoring and analysis of network data became important and with it the field of network forensics. While in traditional computer forensics data is collected and analysed after and as a result of a security incident, in network forensics data is often

collected and analysed with the specific aim to actively detect security intrusions. More recent developments focus on the capture and analysis of volatile computer data (memory forensics), the investigation of mobile devices (mobile device forensics) and the enterprise-wide investigation of security breaches (enterprise forensics). While digital forensic methods are regularly applied in the investigation of criminal cases, civil litigations also make use of the forensic analysis of digital data. This so called electronic discovery or e-dicovery process is often a part of internal compliance investigations in an enterprise context.

4.4.5 Forensics in IT security investigations and its relations to criminal and civil litigations – Heiko Patzlaff

There are specific differences in the application of digital forensic methods for the investigation of security breaches versus its use in litigation.

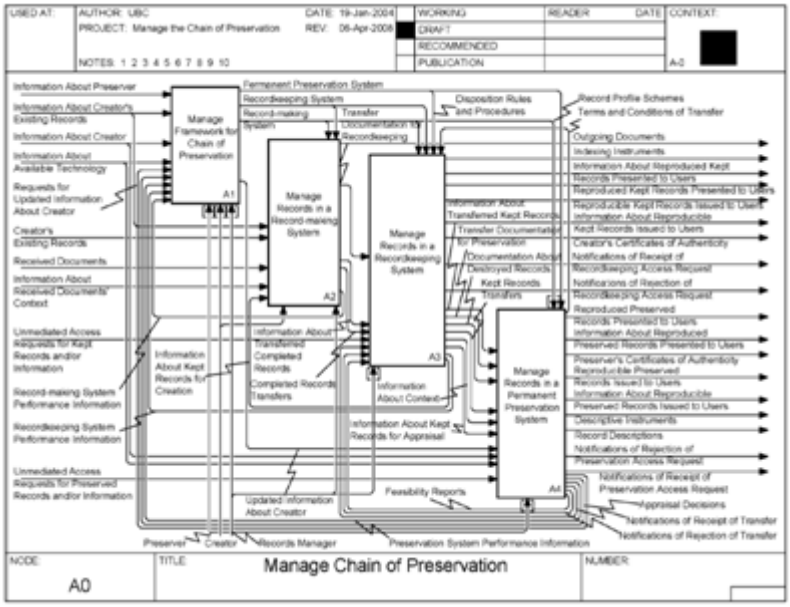
a. IT security investigations are usually not user centric Since the target of a security attack is usually a computer system inside a company and the attacker is an outsider, data produced by the user of the computer system is not relevant to the investigation. The aim is to reconstruct the activities of the attacker. The analysis of logs and timestamps plays a central role. While user activity traces might be important for and therefore part of the investigation, this has fewer data protection and data privacy implications than the analysis of user generated content such as emails or office documents.

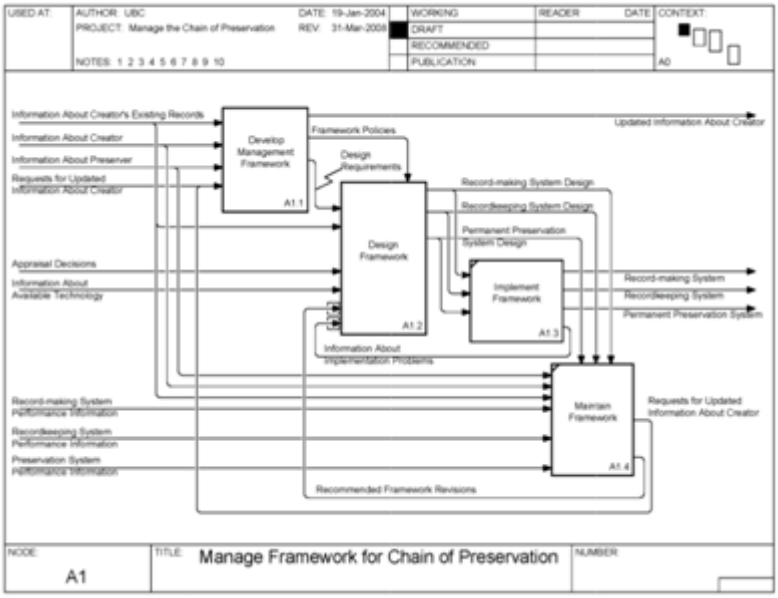
b. IT security investigations usually don't lead to litigation Even though typical security breaches are in most countries illegal, the investigation of those breaches usually does not lead to litigation. The reasons are practical since establishing the identity of the attacker is often not possible or cost prohibitive. There are therefore less stringent requirements with respect to the collection, analysis and preservation of data than in digital forensic investigations leading to criminal or civil lawsuits. The main aim of a security forensic investigation is therefore usually not to identify the attacker but to establish the root cause of why a security breach was possible and the damage that was done.

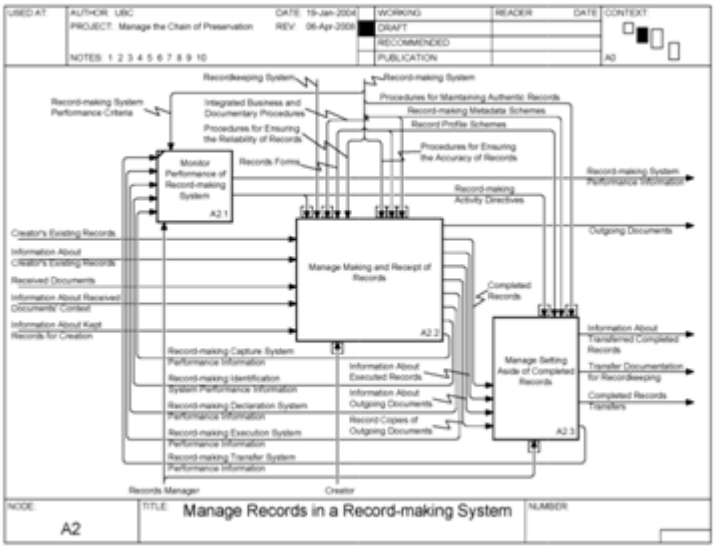
4.4.6 Current trends and challenges

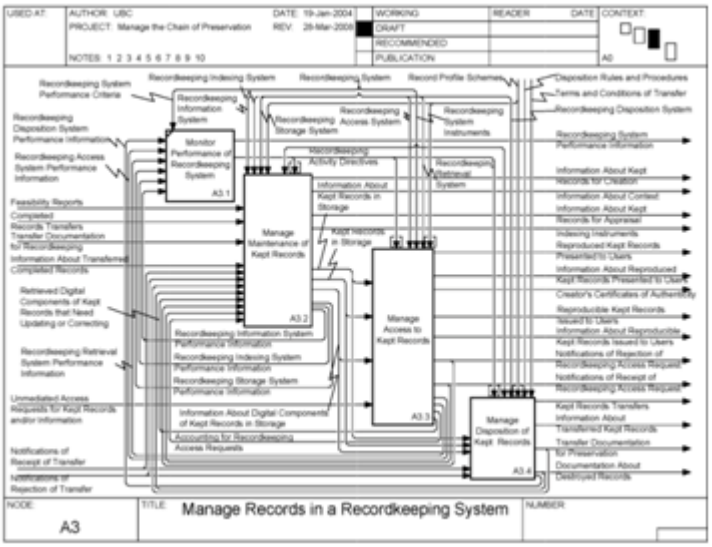
With the growing loss of effectiveness of traditional, signature-based security controls such as anti-virus and the advent of campaign style attacks against company intellectual properties (advanced persistent threats) in recent years, the need for new ways to conduct digital forensic investigations has become apparent. The need for large-scale investigations of hundreds or thousands of computers has lead to the field of enterprise forensics and brought the introduction of new pro-active methodologies such as malware hunting, where company-wide searches of computers for the presence of specific objects or anomalies are conducted in order to identify compromised computer nodes. This has lead to new legal questions related to the protection of user data and privacy. While traditional investigations of single computer nodes are both limited in scope and bound to specific indicators of a successful security breach of the computer in question, these new investigations are often conducted based on much less clear compromise indicators and with a much wider scope. They might also extend across multiple countries and jurisdictions. Another challenge arises with the new trend of user owned devices (bring your own device, BYOD) where company and user data are not well separated and again questions related to user data and privacy emerge.

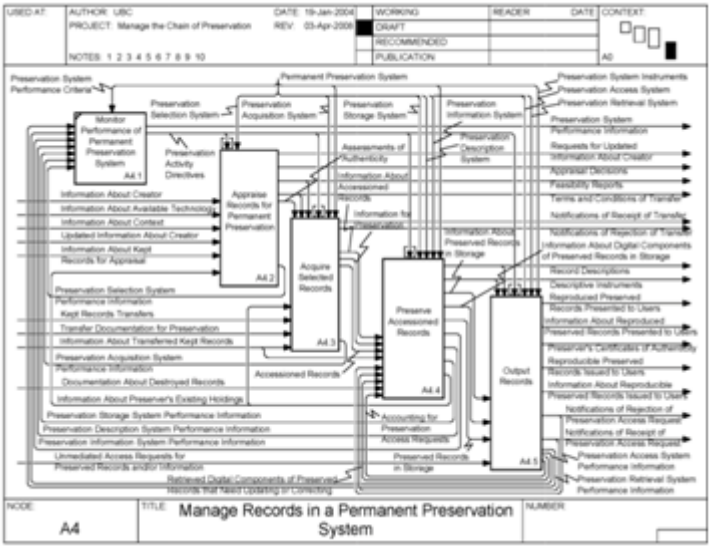
4.4.7 Appendix – Key diagrams from the COP Model






Manage Records in a Record-making System
A2


Manage Records in a Recordkeeping System
A3


Manage Records in a Permanent Preservation System
A4

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