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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 14101

Preference Learning

Edited by

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- Abstract -

This report documents the program and the outcomes of Dagstuhl Seminar 14101 "Preference Learning". Preferences have recently received considerable attention in disciplines such as machine learning, knowledge discovery, information retrieval, statistics, social choice theory, multiple criteria decision making, decision under risk and uncertainty, operations research, and others. The motivation for this seminar was to showcase recent progress in these different areas with the goal of working towards a common basis of understanding, which should help to facilitate future synergies.

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Johannes Fürnkranz Eyke Hüllermeier

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The topic of "preferences" has recently attracted considerable attention in Artificial Intelligence (AI) research, notably in fields such as autonomous agents, non-monotonic reasoning, constraint satisfaction, planning, and qualitative decision theory. Preferences provide a means for specifying desires in a declarative way, which is a point of critical importance for AI. Drawing on past research on knowledge representation and reasoning, AI offers qualitative and symbolic methods for treating preferences that can reasonably complement hitherto existing approaches from other fields, such as decision theory. Needless to say, however, the acquisition of preference information is not always an easy task. Therefore, not only are modeling languages and suitable representation formalisms needed, but also methods for the automatic learning, discovery, modeling, and adaptation of preferences.

It is hence hardly surprising that methods for learning and constructing preference models from explicit or implicit preference information and feedback are among the very recent research trends in disciplines such as machine learning, knowledge discovery, information



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Figure 1 Preference and learning and related research areas within machine learning (blue), information retrieval (purple), applied mathematics (turquoise), and the decision sciences (green).

retrieval, statistics, social choice theory, multiple criteria decision making, decision under risk and uncertainty, operations research, and others. In all these areas, considerable progress has been made on the representation and the automated learning of preference models. The goal of this Dagstuhl Seminar was to bring together international researchers in these areas, thereby stimulating the interaction between these fields with the goal of advancing the state-of-the-art in preference learning. Topics of interest to the seminar include

- quantitative and qualitative approaches to modeling preference information;
- **—** preference extraction, mining, and elicitation;
- methodological foundations of preference learning (learning to rank, ordered classification, active learning, learning monotone models, ...)
- inference and reasoning about preferences;
- mathematical methods for ranking;
- applications of preference learning (web search, information retrieval, electronic commerce, games, personalization, recommender systems, ...).

The main goal of the seminar was to advance the state-of-the-art in preference learning from a theoretical, methodological as well as application-oriented point of view. Apart from that, however, we also hope that the seminar helped to further consolidate this research field, which is still in an early stage of its development. Last but not least, our goal was to connect preference learning with closely related fields and research communities (cf. Figure 1).

In order to achieve these goals, the program featured the following components:

- Monday was filled with 6 tutorial-type introductory talks about the use of preferences and the view on preference learning in the areas of machine learning, recommender systems, multi-criteria decision making, business and economics, artificial intelligence, and social choice, with the goal of familiarizing the members of the different communities with the basics of the other fields.
- Ten sessions were devoted to contributed presentations, each one with enough extra time for discussion. In case we ran over time, we gave priority to discussions. We were also able to flexibly integrate a few impromptu talks by participants.
- Two discussion sessions on Tuesday and Thursday afternoon were devoted to discussion how to establish closer connections between the different research areas that participated in this seminar.
- Wednesday afternoon featured a hike and an excursion to Trier with some wine tasting.

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3 Introductory Talks

The program started on Monday with an entire day of introductory talks that had the goal of familiarizing the audience with each other's backgrounds.

- E. Hüllermeier, J. Fürnkranz: Preference Learning as a Machine Learning Discipline
- D. Jannach: Preference Learning in Recommender Systems an Application-oriented Perspective
- R. Słowiński: Preference Modeling in Operational Research & Multiple Criteria Decision Aiding
- D. Baier: Preference Learning in Business and Economics: a Tutorial on Conjoint Analysis
- K. Brent-Venable, F. Rossi, T. Walsh, J. Lang: Preferences in Artificial Intelligence and Social Choice

3.1 Preference Learning as a Machine Learning Discipline

Eyke Hüllermeier (Uni Marburg) and Johannes Fürnkranz (TU Darmstadt)

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The primary goal of this tutorial talk is to provide a survey of the field of preference learning in its current stage of development. Preference learning refers to the task of learning to predict an order relation on a collection of objects (alternatives). In the training phase, preference learning algorithms have access to examples for which the sought order relation is (partially) known. Depending on the formal modeling of the preference context and the alternatives to be ordered, one can distinguish between various problems types, most notably object ranking and label ranking. Both types of problems can be approached either by modeling the binary preference relation directly, or by inducing this relation indirectly via an underlying (latent) utility function.

The presentation will focus on a systematic overview of different types of preference learning problems, methods and algorithms to tackle these problems, the computational complexity of preference learning, and metrics for evaluating the performance of preference models induced from data. Along the way, we shall also try to establish a unified terminology and, moreover, to indicate connections to related research areas as well as potential applications. We will particularly focus on the aspects that are typical for machine learning, such as generalization to unseen data, and the definition of suitable loss functions which on the one hand allow to measure the learning success, and the other hand also provide the learning algorithms with criteria that can be optimized given the available training data.

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3.2 Preference Learning in Recommender Systems – an Application-oriented Perspective

Dietmar Jannach (TU Dortmund, DE)

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 Main reference D. Jannach, M. Zanker, A. Felfernig, G. Friedrich, "Recommender Systems – An introduction," Cambridge University Press, ISBN 9780521493369, 2010.
 URL http://www.recommenderbook.net/

The introductory talk provided an overview of common approaches to building recommender systems. Key techniques such as collaborative filtering and content-based filtering as well as knowledge-based approaches were discussed. A particular focus of the talk was on preference acquisition and learning in the context of recommender systems. The talk ended with a discussion of recent topics in the field, practical challenges, and open issues in the context of the empirical evaluation of recommender systems in research settings.

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3.3 Preference Modeling in Operational Research & Multiple Criteria Decision Aiding

Roman Słowiński (Poznań University of Technology, PL)

Decision problems considered in Operational Research often involve a set of alternatives (actions, objects) having vector evaluations, with the aim of either choosing the best alternative, or ranking them, or classifying them into some pre-defined and ordered classes. The vector evaluations correspond to multiple dimensions on which the alternatives are described: a dimension can be either a judgment of a voter, or an evaluation criterion, or a probability of an outcome. The three types of dimensions correspond to decision problems considered within Social Choice Theory, Multiple Criteria Decision Aiding, and Decision under Risk & Uncertainty, respectively. As evaluations on multiple dimensions are usually in conflict, the challenge consists in aggregation of evaluations on these dimensions, so as to arrive at a satisfactory recommendation formulated in terms of either the best choice, or ranking, or classification. For all these decision problems, the only objective information that stems from the problem formulation is the dominance relation in the set of alternatives. The dominance relation is, however, a partial preorder, thus it leaves many alternatives non-comparable. To enrich this relation and comparability between alternatives, a particular decision maker (DM) has to reveal her/his value system through some preference statements. This information is then used to construct/learn a preference model of the DM. This model can have the form of a synthetic value (utility) function, or a binary (outranking) relation, or a set of monotonic "*if*..., *then*..." decision rules. The preference model is inducing a preference relation on the set of alternatives. A proper exploitation of this relation leads to a recommendation [1].

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We concentrate on reviewing methodologies for constructing/learning the above mentioned three types of preference models in Multiple Criteria Decision Aiding (MCDA). Moreover, we are focusing on constructing preference models from preference information provided by the DM in terms of decision examples, e.g., pairwise comparisons of some alternatives, or assignment of some alternatives to classes, or rank related requirements, or comparisons of pairs of some alternatives with respect to intensity of preference. For preference models having the form of a value function or an outranking relation, we describe a representative MCDA methodology, called Robust Ordinal Regression (ROR). ROR implements an interactive preference construction paradigm, which should be perceived as a mutual learning of the model and the DM [2, 3]. An important feature of ROR is identification of all instances of the preference model that are compatible with the input preference information – this permits to draw robust conclusions regarding DM's preferences when any of these models is applied on the considered set of alternatives. As value function models may have more or less complex form, getting a parsimonious model, adequate to the complexity of the provided preference information, is desirable.

Another aspect related to decision examples constituting the preference information is inconsistency of these examples with respect to dominance. To deal with, a Dominancebased Rough Set Approach (DRSA) has been proposed, that aims at structuring preference information into sufficiently consistent and excessively inconsistent, prior to induction of monotonic "if ..., then ..." decision rules considered as a logical preference model [3].

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3.4 Preference Learning in Business and Economics: a Tutorial on Conjoint Analysis

Daniel Baier (BTU Cottbus, DE)

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The tutorial gives an overview on conjoint analysis, the most widely applied methodology for measuring and analyzing consumer preference in business and economics. The underlying concepts of the five steps (1) Selection of attributes and levels, (2) Design of hypothetical alternatives, (3) Collection of preferential responses, (4) Estimation of model parameters, (5) Choice prediction are discussed and illustrated by examples. A recent overview on 1.899 commercial applications of conjoint analysis are used to discuss open problems and current solutions. 4 Contributed Talks

4.1 Online Learning Over the Permutahedron: Full Information and Bandit Settings

Nir Ailon (Technion – Haifa, IL)

Consider the following game: There is a fixed set V of n items. At each step an adversary chooses a score function $s_t : V \mapsto [0, 1]$, a learner outputs a ranking of V, and then s_t is revealed. The learner's loss is the sum over $v \in V$, of $s_t(v)$ times v's position (0th, 1st, 2nd, ...) in the ranking. This problem captures, for example, online systems that iteratively present ranked lists of items to users, who then respond by choosing one (or more) sought items. The loss measures the users' burden, which increases the further the sought items are from the top. It also captures a version of online rank aggregation.

We present an algorithm of expected regret $O(n\sqrt{OPT} + n^2)$, where OPT is the loss of the best (single) ranking in hindsight. This improves the previously best known algorithm of Suchiro et. al (2012) by saving a factor of $\Omega(\sqrt{\log n})$. We also reduce the per-step running time from $O(n^2)$ to $O(n \log n)$. We provide matching lower bounds.

In the bandit setting, the score functions s_t are not observed. Only the losses are observed. For this setting we present an algorithm with regret $O(n^{3/2}\sqrt{T})$ with per step running time $O(n^3)$. This trades off with a previous result of Cesa-Bianchi et al. who devise an algorithm of regret $O(n\sqrt{T\log n})$ using an algorithm that requires computing a nonnegative matrix permanent (a #P-Hard problem) at each step.

4.2 Efficient Optimization Approaches for Pairwise Ranking Losses

Antti Airola (University of Turku, FI)

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Joint work of Airola, Antti; Pahikkala, Tapio; Salakoski, Tapio

Main reference A. Airola, T. Pahikkala, T. Salakoski, "Training linear ranking SVMs in linearithmic time using red-black trees," Pattern Recognition Letters. 32(9):1328–1336, 2011.

 $\textbf{URL}\ http://dx.doi.org/10.1016/j.patrec.2011.03.014$

Straightforward approaches to minimizing pairwise ranking losses on scored data lead to quadratic costs. We demonstrate, that for the special cases of pairwise hinge loss (RankSVM) and pairwise least-squares loss (RankRLS), better scaling can be achieved by modeling the preferences only implicitly using suitable data structures.

Software implementations are available at

- http://staff.cs.utu.fi/~aatapa/software/RankSVM/(RankSVM) and
- https://github.com/aatapa/RLScore(RankRLS).

4.3 Revisiting Probabilistic Matrix Factorisation in Light of the Observed Ratings

Cédric Archambeau (Amazon CS Berlin GmbH, DE)

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 Joint work of Archambeau, Cédric; Balaji Lakshminarayanan; Guillaume Bouchard
 Main reference B. Lakshminarayanan, G. Bouchard, C. Archambeau, "Robust Bayesian Matrix Factorisation," in Proc. of the 14th Int'l Conf. on Artificial Intelligence and Statistics (AISTAT'11), JMLR Proceedings, Vol. 15, pp. 425–433, JMLR.org, 2011.

 URL http://www.jmlr.org/proceedings/papers/v15/lakshminarayanan11a/lakshminarayanan11a.pdf

We analyse the noise arising in collaborative filtering when formalised as a probabilistic matrix factorisation problem. We show empirically that modelling row- and column-specific variances is important, the noise being in general non-Gaussian and heteroscedastic. We also advocate for the use of a Student-t priors for the latent features as the standard Gaussian is included as a special case. We derive several variational inference algorithms and estimate the hyperparameters by type-II maximum likelihood. Experiments on real data show that the predictive performance is significantly improved.

4.4 Bayesian Methods for Conjoint Analysis-Based Predictions: Do We Still Need Latent Classes?

Daniel Baier (BTU Cottbus, DE)

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Daniel Baier
 Main reference D. Baier, "Bayesian Methods for Conjoint Analysis-Based Prediction: Do We Still Need Latent Classes?" in W. Gaul et al., (eds.), German-Japanese Interchange of Data Analysis Results, Part II; Studies in Classification, Data Analysis, and Knowledge Organization, Vol. 47, 103–113, Springer, 2014.
 URL http://dx.doi.org/10.1007/978-3-319-01264-3_9

Recently, more and more Bayesian methods have been proposed for modeling heterogeneous preference structures of consumers (see, e.g.,[1, 2, 3]) Comparisons have shown that these new methods compete well with the traditional ones where latent classes are used for this purpose (see [4] for an overview on these traditional methods). This applies especially when the prediction of choices among products is the main objective (e.g. [5, 6, 7, 8] with comparative results). However, the question is still open whether this superiority still holds when the latent class approach is combined with the Bayesian one. This paper responds to this question. Bayesian methods with and without latent classes are used for modeling heterogeneous preference structures of consumers and for predicting choices among competing products. The results show a clear superiority of the combined approach over the purely Bayesian one. It seems that we still need latent classes for conjoint analysis-based predictions.

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4.5 Preference-based Online Learning using Statistical Models: The Case of Mallows

Róbert Busa-Fekete (Universität Marburg, DE)

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 Joint work of Busa-Fekete, Róbert; Szörényi, Balázs; Hüllermeier, Eyke;

We address the problem of rank elicitation assuming that the underlying data generating process is characterized by a probability distribution on the set of all rankings (total orders) of a given set of items. Instead of asking for complete rankings, however, our learner is only allowed to query pairwise preferences. Using information of that kind, the goal of the learner is to reliably predict properties of the distribution, such as the most probable top-item, the most probable ranking, or the distribution itself. More specifically, learning is done in an online manner, and the goal is to minimize sample complexity while guaranteeing a certain level of confidence.

4.6 F-Measure Maximization for Thresholding a Ranking

Krzysztof Dembczyński (Poznań University of Technology, PL)

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 Krzysztof Dembczyński
 Joint work of Dembczyński, Krzysztof; Busa-Fekete, Róbert; Waegeman, Willem; Cheng, Weiwei; Hullermeier, Evke

In many applications we are interested in retrieving top k elements from a ranking. There is, however, a problem how to determine k which can be given explicitly or defined through a threshold on utility values. The F-measure is commonly used to determine such a threshold in binary classification. When assuming independence of the ranked elements the F-measure satisfies the so-called probability ranking principle [4], i.e., the elements above the threshold have greater marginal probabilities of relevance than the elements below the threshold. We show how the situation changes in a general case without imposing the independence assumption [2]. We also discuss two frameworks for F-measure maximization [6]: the decisiontheoretic approach and the empirical utility maximization. We also shortly address the problem of on-line maximization of the F-measure.

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4.7 Cautious Label Ranking by Label-wise Decomposition

Sébastien Destercke (Technical University of Compiegne, FR)

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Sébastien Destercke
Joint work of Destercke, Sébastien; Michael Poss; Marie-Helene Masson

In this talk, we present a method that aims at providing partial predictions in the setting of label ranking. We propose to do it through a label-wise decomposition scheme and to use imprecise probabilistic model to obtain the partial predictions. After a brief reminder of the imprecise probabilistic setting, we provide some details about our method and the way partial predictions can be obtained in a tractable way. In particular, we provide efficient methods to compute the Pareto-set of an assignment problem with imprecise costs described by convex sets (resulting from the imprecise probabilistic models). The method extends the recently proposed labelwise Decomposition of Cheng et al.[1] to accomodate partial predictions.

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4.8 Exploiting Monotonicity Constraints for Arctive Learning in Ordinal Classification

Ad J. Feelders (Utrecht University, NL)

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 Ad J. Feelders

 Joint work of Feelders, Ad J.; Barile, Nicola; Soons, Pieter
 Main reference N. Barile, A. J. Feelders, "Active Learning with Monotonicity Constraints," in Proc. of the 2012 SIAM Int'l Conf. on Data Mining (SDM'12), pp. 756–767, 2012.
 URL http://dx.doi.org/10.1137/1.9781611972825.65

In many applications of data mining it stands to reason that the response variable is increasing in the attributes. For example, the probability of acceptance for a loan increases with disposable income. Such relations between response and attribute are called monotone. If the class label of an object is given, then monotonicity may allow the labels of other objects to be inferred. For instance, knowing that applicant A is rejected, we can infer that applicants who score worse than A on all criteria should be rejected as well.

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Given a collection of unlabeled attribute vectors, the question that arises is: for which vector should we request the class label from the expert, so that we can infer as many labels as possible?

We use the monotonicity constraint to augment the training sample with examples whose label can be inferred. The quality of a query strategy is measured by the predictive performance of models constructed on the resulting training sample. We consider a "monotone oracle" as well as an oracle that may produce labels that violate the monotonicity constraint.

The query strategies are evaluated on artificial data as well as publicly available real-life data sets.

4.9 A Decision-Maker Without Preferences

Andreas Geyer-Schulz (KIT – Karlsruher Institut für Technologie)

In this contribution we analyze a decision-maker without preferences. A decision-maker without preferences is a decision-maker which chooses an element of a choice set with equal probability. The problem is trivial, if the choice set is known a-priori. However, if the choice set (and its size n) is not known, we construct an (infinite) series of probability spaces and study the probability distribution of potential choice variants of k items out of n. We observe that, depending on n, rank reversals of choice variants occur, although the decision-maker acts completely rational (for small n). For large n, the order of the choice variants becomes stable, no further anomalies occur. We link this to the axiom of the violation of the independence of irrelevant alternatives in decision-theory. And in addition, we refer to research in marketing on the way consumer choices are modelled by a subsequent restriction of the choice set and the effect on branding on the human brain.

4.10 ConjointBench: Setting up and Analyzing Simple Conjoint Studies

Joachim Giesen (Universität Jena, DE)

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Joint work of Giesen, Joachim; Mueller, Jens K.; Kaiser, Markus
URL http://theinf2.informatik.uni-jena.de/Software/ConjointBench.html

Conjoint analysis is a family of techniques that originated in psychology and later became popular in market research. The main objective of conjoint analysis is to measure an individual's or a population's preferences on a class of options that can be described by parameters and their levels. In choice based conjoint analysis preference data are obtained by observing test persons' choices on small subsets of the options. There are many ways to analyze choice-based conjoint analysis data. A simple but powerful approach is a reduction to a linear binary classification problem. We have implemented this reduction and use a linear support vector machine for solving the resulting classification problem. The implementation is available through the ConjointBench at our homepage at the university in Jena. The ConjointBench allows to set up simple conjoint analysis studies, to distribute a choice based questionnaire in a Doodle like manner, and to analyze the elicited data using a support vector machine.

4.11 Comparing Preference Learning with Robust Ordinal Regression and Multicriteria Customer Satisfaction Analysis

Salvatore Greco (University of Portsmouth, GB)

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Multiple Criteria Decision Aiding (MCDA) offers a diversity of approaches designed for providing the decision maker (DM) with a recommendation concerning a set of alternatives (items, actions) evaluated from multiple points of view, called criteria. This presentation aims at drawing the attention of the Preference Learning (PL) community upon recent advances in a representative MCDA methodology, called Ordinal Regression, focalizing on two main issues: Robust Ordinal Regression (ROR), and measuring and analyzing customer satisfaction concerning a product through the MUSA-INT method. ROR learns by examples in order to rank a set of alternatives, thus it deals with a problem similar to that one considered by Preference Learning. ROR implements, however, an interactive preference construction paradigm, which should be perceived as mutual learning of the preference model and the DM, and not as discovering of a preference model preexisting in the DM's mind. The talk clarifies the specific interpretation of the concept of preference learning adopted in ROR and MCDA, and shows similarities and differences with respect to the usual concept of preference learning considered within PL. This comparison concerns the structure of the considered problem, the types of admitted preference information, the form of the employed preference models, the ways of exploiting them, and, finally, the techniques applied to arrive at a final ranking. MUSA-INT methodology generalizes the MUSA (MUlticriteria Satisfaction Analysis) method. MUSA is a preference disaggregation method that, following the principle of ordinal regression analysis, finds an additive utility function representing both the comprehensive satisfaction level of a set of customers and a marginal satisfaction level with respect to each criterion. Differently from MUSA, MUSA-INT takes also into account positive and negative interactions among criteria, similarly to the multicriteria method UTAGMS-INT. MUSA-INT accepts evaluations on criteria with different ordinal scales which do not need to be transformed into a unique cardinal scale prior to the analysis. Moreover, instead of a single utility function, MUSA-INT can also take into account a set of utility functions representing customers' satisfaction, adopting the robust ordinal regression methodology. An illustrative example shows how the proposed methodology can be applied on a customers survey.

4.12 Multidimensional Unfolding and Clustering of Preferences: A New Simulation Design

Willem J. Heiser (Leiden University, NL)

Unfolding models are built on the concept of single-peaked preference functions that have different locations on a scale or in a space of options. The key idea is to construct a joint scale or a joint space that contains two kinds of points: one set of points for the options, and another set of points for the judges, where the latter are called ideal points because they represent the position of the peak in the single-peaked preference functions, and hence

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the ideal option that a judge could imagine. The objective of multidimensional unfolding then is to locate the ideal points and the option points in the joint space, in such a way that their inter-point Euclidean distances are inversely related to the preferences. We discuss a particular unfolding method and program called PREFSCAL, based on least squares and optimal data transformation. Next, we present a clustering method for preferences, called Cluster Component Analysis (CCA), which is based on the Kemeny distance between rankings, and show how it can be combined with the unfolding representation. We also outline a new simulation design for generating clusters of rankings from central rankings that satisfy an unfolding model. In this type of design, we can keep the dispersion within clusters and the amount of overlap between clusters under control, while also generating noise rankings which do not satisfy the unfolding model. Our first results indicate that CCA can recover the original central rankings very well, and that the unfolding representation is also recoverable.

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4.13 Preferences in an Open World: Perspectives for Preference Learning

Ulrich Junker (Biot, DE)

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 Ulrich Junker
 Main reference
 U. Junker, "Preferences in an Open World," in Proc. of the 1st Int'l Conf. on Algorithmic Decision Theory (ADT'09), LNCS, Vol. 5783, pp. 215-224, Springer, 2009.
 URL http://dx.doi.org/10.1007/978-3-642-04428-1

Decision making may involve multiple viewpoints which are comparing the given options according to different preference relations. Examples are the viewpoints of multiple agents in group decision making or the viewpoints imposed by different criteria in multi-criteria decision making. The talk studies questions that arise when multiple viewpoints are merged into a single viewpoint over a combinatorial criteria space. The talk revisits a preference model presented at the ADT 2009 conference and explores its possibilities for preference learning.

The merging of viewpoints requires an aggregation of the preferences of the individual viewpoints, for example by adopting a ceteris-paribus semantics. Preferences can thus be aggregated in a purely deductive way without requiring any additional learning step. According to this method, it is sufficient to learn the preferences of the individual agents in order to predict the decisions of a group of agents.

However, the strict ceteris-paribus semantics may turn out to be too restrictive. What happens if agents accurately follow their individual preferences in individual situations, but the decision made by a group of agents contradicts the predictions made by the preference aggregation? Such a scenario permits the learning of a new preference over the merged

J. Fürnkranz, E. Hüllermeier, C. Rudin, S. Sanner, and R. Słowiński

viewpoint that states that the observed decision is strictly preferred to the decision predicted under the ceteris-paribus semantics. This new preference will conflict with the ceteris-paribus preferences.

We present an approach that aggregates preference relations while applying the ceterisparibus principle as a default rule instead of a strict rule. More specific preference statements over the merged viewpoints can thus override preferences resulting from aggregating the preferences of the individual viewpoints. The resulting preference model provides the same predictions as the standard model if no observation contradicts these predictions, but is able to accommodate to situations where the observations contradict the predicted behaviour. It thus provides new perspectives for preference aggregation and preference learning in combinatorial domains.

4.14 Rank Loss Minimization with Pointwise Surrogates

Wojciech Kotłowski (Poznań University of Technology, PL)

We consider the problem of rank loss minimization or, equivalently, maximization of AUC, in bipartite ranking and multilabel classification. Since the complexity of these problems is quadratic in the number of training examples/labels, it is tempting to ask how much can be done by minimizing a simple pointwise (univariate) loss function, as done by standard classification methods, as a surrogate. We show that weighted (cost-sensitive) versions of standard margin-based surrogates, such as exponential or logistic loss, are consistent for rank loss minimization. Instead of directly proving convergence, we give a stronger result by deriving regret bounds and convergence rates. The proposed losses suggest efficient and scalable algorithms, which are tested experimentally. We also extend our results to the case of rank loss minimization in multipartite ranking (ordinal regression).

4.15 Graded Multilabel Classification by Pairwise Comparisons

Eneldo Loza Mencía (TU Darmstadt, DE)

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The task in multilabel classification is to predict for a given set of labels whether each individual label should be attached to an instance or not. Graded multilabel classification generalizes this setting by allowing to specify for each label a degree of membership on an ordinal scale. This setting can be frequently found in practice, for example when movies or books are assessed on a one-to-five star rating in multiple categories.

In this paper, we propose to reformulate the problem in terms of preferences between the labels and their scales, which then be tackled by learning from pairwise comparisons. We present three different approaches which make use of this decomposition and show on three datasets that we are able to outperform baseline approaches.

In particular, we show that our solution, which is able to model pairwise preferences across multiple scales, outperforms a straight-forward approach which considers the problem as a set of independent ordinal regression tasks.

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4.16 A Brief Survey on Learning Compact Representations of Preferences over a Combinatorial Domain

Jérôme Mengin (Paul Sabatier University – Toulouse, FR)

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We consider orderings over a combinatorial domain, for instance a catalog where items are defined by a number of options, so that the number of available items is exponential in the number of options. Can we learn an ordering of the items from observations of users navigating in this catalog, in order to guide future users of the catalog ? We survey a few results on learning two types of compact representations for this ordering.

Generalized additive utilities rank the items according to the sum of their scores on a limited number of subsets of the options. Such a representation is easy to learn from examples of pairwise comparisons when the structure (the subsets of options) are known, but learning the structure is hard.

Conditional preference rules of the form "if X is the case, then this value for option Y is preferred to that value" can also be used to compactly represent preferences. Reasoning with such rules can be tractable if the rules are associated with some structure over the set of options. For instance, if there is an importance, possibly partial, ordering over the set of variables, then pairwise comparisons can be done in linear time, and learning the rules can also be done in polynomial time from observations of such pairwise comparisons. CP-nets, in which is a directed graph, usually acyclic, over the set of variables represent preferential dependencies, enable fast retrieval of optimal (undominated) items, and can be learnt efficiently from observations of optimal items.

4.17 Learning Ordinal Sorting Models from Large Learning Sets: A Multicriteria Decision Aid Perspective

Vincent Mousseau (Ecole Centrale Paris, FR)

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Joint work of Mousseau, Vincent; Pirlot, Marc; Sobrie, Olivier

Main reference O. Sobrie, V. Mousseau, M. Pirlot, "Learning a Majority Rule Model from Large Sets of

Assignment Examples," in Proc. of the 3rd Int'l Conf. on Algorithmic Decision Theory (ADT'13), LNCS, Vol. 8176, pp. 336–350, Springer, 2013.

 ${\tt URL \ http://dx.doi.org/10.1007/978-3-642-41575-3_26}$

Multiple criteria sorting methods assign alternatives to predefined ordered categories. The Majority Rule Sorting model (MR-Sort) is an outranking based sorting method corresponding to a simplified version of Electre Tri. Learning the parameters of a MR-Sort model through linear programming requires the use of binary variables. In the context of preference learning where large sets of alternatives and numerous attributes are involved, such an approach is not an option in view of the large computing times implied. Therefore, we propose a new metaheuristic designed to learn the parameters of an MR-Sort model. This algorithm works in two phases that are iterated. The first one consists in solving a linear program determining the weights and the majority threshold, assuming a given set of profiles. The second phase runs a metaheuristic which determines profiles for a fixed set of weights and a majority threshold. The presentation focuses on the metaheuristic and reports the results of numerical tests, providing insights on the algorithm behavior. The perspective of handling large datasets to learn preference models is discused in the context of Multicriteria Decision Aiding.

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4.18 Making Decisions with High-Level Preferences and User-Centric Principles

Ingrid Oliveira de Nunes (Federal University of Rio Grande do Sul, BR)

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 Joint work of Nunes, Ingrid Oliveira de; Luck, Michael; Miles, Simon; Barbosa, Simone; Lucena, Carlos
 Main reference I. O. de Nunes, "User-centric Preference-based Decision Making," PhD Thesis, Pontifícia Universidade Católica do Rio de Janerio (PUC-Rio), 2012.
 URL http://www.inf.ufrgs.br/~ingridnunes/publications/0912914_2012_Completa.pdf

Choosing from a set of available options often requires resolution of trade-offs but it can be unfeasible for humans to carefully evaluate each option of a large set due to the required time and cognitive effort. Consequently, they are often unsatisfied with their choices. Software systems can support human decision making or even automate this process, but there are many challenges associated with the provision of such support. In this talk, I will first introduce a new preference meta-model founded on a study of how humans express preferences, allowing the representation of high-level preferences. Then, I will introduce an automated decision making technique, which chooses an option from a set available based on preferences expressed in a language based on the meta-model, exploiting natural-language terms. This technique makes decisions with the incorporation of psychology principles, which concern how humans make decisions, as the provided preferences are typically not enough to resolve trade-offs among available options. Finally, I will present an explanation generation technique, which uses models built by the decision making technique to justify choices, and follows guidelines and patterns derived from a study of choice explanation.

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4.19 Algorithmics of Tensor-Based Preference Learning

Tapio Pahikkala (University of Turku, FI)

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- © Tapio Pahikkala
- Main reference T. Pahikkala, "Fast Gradient Computation for Learning with Tensor Product Kernels and Sparse Training Labels," in Proc. of the IAPR Int'l Workshop on Structural and Syntactic Pattern Recognition (S+SSPR 2014), to appear; preprint available from the author's webpage.
 URL http://staff.cs.utu.fi/~aatapa/publications/Pahikkala2014SSSPR.pdf
 - **UKL** http://stan.cs.utu.ii/~aatapa/publications/1 anikkaia20145551 ft.pub

We consider the problem of learning utility functions and rankings with paired inputs and tensor-based kernel functions defined on such inputs. With paired inputs, we refer to the ones consisting of a condition and an object part. The condition being, for example, a query object given at prediction time, the learned model assigns scores for a set of target objects also given at prediction time, that indicate the conditional utility of the targets for the query. We present a new learning algorithm for the considered setting whose computational efficiency is improved with tensor-algebraic optimization.

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4.20 A Borda Count for Collective Sentiment Analysis

Francesca Rossi (University of Padova, IT)

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Joint work of Grandi, Umberto; Loreggia, Andrea; Rossi, Francesca; Saraswat, Vijay;

Main reference U. Grandi, A. Loreggia, F. Rossi, V. Saraswat, "From Sentiment Analysis to Preference

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 ${\tt URL}\ {\tt http://www.cs.uic.edu/pub/Isaim2014/WebPreferences/ISAIM2014_CSC_Grandi_etal.pdf$

Sentiment analysis assigns a positive, negative or neutral polarity to an item or entity, extracting and aggregating individual opinions from their textual expressions by means of natural language processing tools. In this paper we observe that current sentiment analysis techniques are satisfactory in case there is a single entity under consideration, but can lead to inaccurate or wrong results when dealing with a set of possibly correlated items. We

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argue in favor of importing techniques from voting theory and preference aggregation to provide more accurate definitions of the collective sentiment for a set of multiple items. We propose a notion of Borda count which combines individuals' sentiment and preference information, we show that this class of rules satisfies a number of properties which have a natural interpretation in the sentiment analysis domain, and we evaluate its behavior when faced with highly incomplete domains.

4.21 Exact Bayesian Pairwise Preference Learning and Inference in Expressive Models

Scott Sanner (NICTA – Canberra, AU)

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 Joint work of Sanner, Scott; Abbasnejad, Ehsan
 Main reference S. Sanner, E. Abbasnejad, "Exact Bayesian Pairwise Preference Learning and Inference in Expressive Models," NIPS Workshop on Choice Models and Preference Learning, 2011.

URL http://users.cecs.anu.edu.au/~sguo/cmpl2011_submission_14.pdf

In Bayesian approaches to utility learning from preferences, the objective is to infer a posterior belief distribution over an agent's utility function based on previously observed agent preferences. From this, one can then estimate quantities such as the expected utility of a decision or the probability of an unobserved preference, which can then be used to make or suggest future decisions on behalf of the agent. However, there remains an open question as to how one can represent beliefs over agent utilities, perform Bayesian updating based on observed agent pairwise preferences, and make inferences with this posterior distribution in an exact, closed-form. In this paper, we build on Bayesian pairwise preference learning models under the assumptions of linearly additive multi-attribute utility functions and a bounded uniform utility prior. These assumptions lead to a posterior form that is a uniform distribution over a convex polytope for which we then demonstrate how to perform exact, closed-form inference w.r.t. this posterior, i.e., without resorting to sampling or other approximation methods.

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4.22 Preferences, Invariances, Optimization

Michèle Sebag (University of Paris South XI, FR)

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 Joint work of Loshchilov, Ilya; Schoenauer, Marc; Sebag, Michèle;

Some optimization settings deal with the user in the loop (a.k.a. interactive optimization) or with expensive ill-posed optimization objectives (e.g. in numerical engineering where the optimization objective is computed using Finite Element methods).

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In such settings, the number of optimization queries should be minimized, and one way to do so is to learn an approximation of the optimization objective, referred to as surrogate model.

Note that replacing the optimization objective F with g(F), with g any monotonous function, does not harm the optimization goal. Accordingly, the surrogate model of F can be learned using preference learning.

The talk will describe how the tight integration of preference learning and the distributionbased optimization algorithm CMA-ES achieves a black-box optimization algorithm which is invariant under monotonous transformations of the optimization objective, and affine transformations of the feature space.

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4.23 Multiresolution Analysis of Incomplete Rankings

Eric Sibony (Télécom Paris Tech, FR)

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 Joint work of Sibony, Eric; Clémençon Stéphan; Jakubowicz, Jérémie
 Main reference S. Clémençon, J. Jakubowicz, E. Sibony, "Multiresolution Analysis of Incomplete Rankings," arXiv:1403.1994v1 [math.ST], 2014.

 URL http://arxiv.org/abs/1403.1994v1

Incomplete rankings on a set of items $1, \ldots, n$ are orderings of the form $a_1 < \ldots < a_k$, with $a_1, \ldots, a_k \subset 1, \ldots, n$ and k < n. Though they arise in many modern applications, only a few methods have been introduced to manipulate them, most of them consisting in representing any incomplete ranking by the set of all its possible linear extensions on $1, \ldots, n$. In this talk, I will introduce a completely novel approach, which allows to treat incomplete rankings directly, representing them as injective words over $1, \ldots, n$. Unexpectedly, operations on incomplete rankings have very simple equivalents in this setting and the topological structure of the complex of injective words can be interpretated in a simple fashion from the perspective of ranking. We exploit this connection here and use recent results from algebraic topology to construct a multiresolution analysis and develop a wavelet framework for incomplete rankings multiresolution analysis on a Euclidean space, and permits to localize the information related to rankings on each subset of items. It can be viewed as a crucial step toward nonlinear approximation of distributions of incomplete rankings and paves the way for many statistical applications, including preference data analysis and the design of recommender systems.

4.24 What is a Decision Problem?

Alexis Tsoukiàs (University Paris-Dauphine, FR)

The presentation introduces a general framework about what is a decision problem. The aim is to provide a theory under which the existing methods and algorithms can be characterised, designed, chosen or justified. The framework shows that 5 features are necessary and sufficient in order to completely describe the whole set of existing methods. It also explains why optimisation remains the general approach under which decision problems are algorithmically considered.

4.25 The Limitations of Convex Surrogate Losses for Learning to Rank

Nicolas Usunier (Technical University of Compiegne, FR)

Part of the research on learning to rank has been driven by its application to search engines, where the training data consists of user queries, candidate documents for each query, and where information on the desired ordering of the documents is obtained from user feedback or paid annotators. In that context, the community has put a great emphasis on designing algorithms that optimize a convex objective function on the training data. The exact form of the convex objective function vary from one algorithm to another, but in all cases the convex objective is used as a computationally tractable surrogate of a pre-specified quality measure of the predicted rankings. The use of convex surrogate approaches is usual in machine learning, and theoretically well- grounded for classification tasks in the sense that optimizing a well-chosen convex objective function asymptotically leads to an optimal classifier. However, as I will show in this talk, such desirable properties of convex surrogate approaches do not extend to ranking: for some of the most common quality measures used to evaluate search engines, it is impossible to generate an optimal ranking function by optimizing a convex objective function. The result implies in particular that many existing algorithms for learning to rank cannot optimize the quality measure they are designed for, even in a favorable asymptotic regime.

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4.26 Incremental Elicitation of Choquet Integrals using Minimax Regret

Paolo Viappiani (UPMC - Paris, FR)

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The Choquet integral is one of the most sophisticated and expressive preference models used in decision theory for multicriteria decision making. It performs a weighted aggregation of criterion values using a capacity function assigning a weight to any coalition of criteria, thus enabling positive and/or negative interactions among criteria and covering an important range of possible decision behaviors. However, the specification of the capacity involves many parameters which raises challenging questions, both in terms of elicitation burden and guarantee on the quality of the final recommendation. In this paper, we investigate the incremental elicitation of the capacity through a sequence of preference queries selected one-by-one using a minimax regret strategy so as to progressively reduce the set of possible capacities until a decision can be made. We propose a new approach designed to efficiently compute minimax regret for the Choquet model. Numerical experiments are provided to demonstrate the practical efficiency of our approach.

4.27 User Modeling with Sparse, Implicit Feedback, e-Shop Data

Peter Vojtáš (Charles University – Prague, CZ)

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 Joint work of Vojtáš, Peter; Peska, Ladislav; Eckhardt, Alan; Horváth, Tomas
 Main reference L. Peska, A. Eckhardt, P. Vojtáš, "UPComp – A PHP Component for Recommendation Based on
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 URL http://dx.doi.org/10.1109/WI-IAT.2011.180

In this report we extend the abstract of our Dagstuhl presentation. The extension consists of related bibliographic references (ordered by time at the end of this report) and short comments on development of our views in the field of preference learning (starting here).

Our previous research was based in fuzzy logic programming, uncertain reasoning and databases. Main impulse came from an anonymous referee at a computer science conference which asked "Where from do your rules (of fuzzy logic programs) come from?" This was an important question also because in this time I have moved to Prague to the Department of Software Engineering and we wanted to contribute to the field (at least from a broader perspective).

Our first reaction was starting research in fuzzy (many valued) inductive logic programming. When looking for data to learn from we used school rating data and were able to find dependencies between ratings of subjects. Immediately, it was clear that our fuzzy values have a comparative meaning, e.g. if physics is at least B or better then Math is at least B or better (in data we learned from). Real life (software engineering relevant) data came from understanding fuzzy degrees as degrees of preferences (inducing ordering). Most challenging were problems with multiple users and recommendation. After a period of research of learning preferences form explicit rating of users, we came to our last point of interest: learning preferences from implicit behavior of a user (typically on an e-shop).

J. Fürnkranz, E. Hüllermeier, C. Rudin, S. Sanner, and R. Słowiński

So now, I can discuss with my software engineering colleagues problems of real applications (which classical UML modeling neglected).

Original Dagstuhl abstract. Our motivation considers recommendation in SME e-shops in area where there is a large competition. In such case users usually do not register and do not rate items. Only information we have are behavioral data collected by PHP scripts. Only direct indicator of preference is purchase. Our model is based on Fagin-Lotem-Naor [1] representation of single user preferences on attributes and aggregating them. Our task is to learn parameters for a many users variant of the FLN model (we have a many users variant of FLN top-k threshold algorithm). But we assumed there is no explicit rating and the only direct preference indicator is purchase! Because of sparseness of data, we take all purchases from all users together (collaborative aspect) and learn some generalization of dependences between their behavior and purchases. We select a t-conorm from a parameterized family and obtain a single rating (user independent) of all behaviors. A new user (test set) behavior is interpreted as explicit ratings of items visited by that user and we learn parameters of FLN model. For each user separately we get a global rating (and hence a ranking) for all items. We evaluate our method on real production data from a travel agency. Finally we report on our other projects, related works and discuss various dimensions of the decision making problem/process.

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4.28 The PeerRank Method

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Main reference T. Walsh, "The PeerRank Method for Peer Assessment," in Proc. of the 21st Europ. Conf. on Artificial Intelligence (ECAI'14), to appear; pre-print available as arXiv:1405.7192v1 [cs.AI]. URL http://arxiv.org/abs/1405.7192v1

I propose the PeerRank method for peer assessment. This constructs a grade for an agent based on the grades proposed by the agents evaluating the agent. Since the grade of an agent is a measure of their ability to grade correctly, the PeerRank method weights grades by the grades of the grading agent. The PeerRank method also provides an incentive for agents to grade correctly. It rewards agents who grade well, and penalises those that grade poorly. As the grades of an agent depend on the grades of the grading agents, and as these grades themselves depend on the grades of other agents, I define the PeerRank method by a fixed point equation similar to the PageRank method for ranking web-pages. I identify some formal properties of the PeerRank method, discuss some examples, compare with related work and evaluate the performance on some synthetic data.

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5 Discussions

The discussion sessions revolved around the use of preferences in various disciplines. As a result of these discussions, we have been able to establish a comprehensive survey of the properties that characterize machine learning, multi-criteria decision aid and conjoint analysis as different approaches to preference learning, showing where these fields share commonalities but also where they differ with respect to underlying assumptions, goals, and methods (cf. Table 1). This discussion helped the participants to broaden their view, and to show more plainly in which way the fields can complement and mutually benefit from each other.

As a concrete follow-up project, we decided to organize a joint special issue in the *European* Journal of Operational Research (EJOR). In order to establish a joint focus, the plan is to use an industrial dataset as a common basis for potential contributions. Thus, the idea is to collect contributions that tackle and exploit the data in different ways, employing the tools of the respective communities.

	PL	MCDA	CA
Problem focus	predictions	user/decision maker	model
User interaction	typically not, yet possible in active learning	constructive, feedback with user in the loop	prior to data collection
Learning domain	population (general- ize across individu- als)	single user	population
Representation of alternatives	feature-based, but also structured, of- ten many (generic) features	monotone, well- engineered criteria, decision space versus criteria space	conjoint structure, well-engineered features
Representation of users	feature-based	no features of the DM used	feature-based
Preference informa- tion	global/holistic, example-based	local and/or global, rich specifications	local and/or global, highlighting heterogeneity
Nature of the data	noisy/probabilistic	consistent, possibly cor- rected	noisy/probabilistic but well designed
Models and model assumptions	possibly weak assump- tions(compensated by massive data)	stronger assumptions, axiomatic foundation	interpretable, often (generalized) linear models
Model interpretation, usage, and expecta- tions	mainly predictive, accurate prediction of decision maker's behavior	mainly constructive or normative, convin- cing explanations of decisions	mainly descriptive, useful descriptions of decision makers
Data availability	data sets massively available (but not always accessible)	limited, user-generated data, no benchmark data	data abounds, many practical projects
Data volume	possibly very large ("big data")	typically small	moderate
Validation, success criteria	accuracy metrics, internal validation on data	user satisfaction (difficult to measure)	external evaluation (business oriented)
Computational aspects	scalability is critical	less critical (but short response time required)	less critical
Application domains	broad but typically not safety-critical (e-commerce, etc.), automated decisions	broad, possibly safety- critical, one-shot de- cisions	business and market- ing

Table 1 Comparison of properties of the disciplines preference learning (PL), multi-criteria decision aiding (MCDA), and conjoint analysis (CA).

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Report from Dagstuhl Seminar 14111

Combinatorics and Algorithmics of Strings

Edited by

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— Abstract -

Strings (aka sequences or words) form the most basic and natural data structure. They occur whenever information is electronically transmitted (as bit streams), when natural language text is spoken or written down (as words over, for example, the Latin alphabet), in the process of heredity transmission in living cells (through DNA sequences) or the protein synthesis (as sequence of amino acids), and in many more different contexts. Given this universal form of representing information, the need to process strings is apparent and is actually a core purpose of computer use. Algorithms to efficiently search through, analyze, (de-)compress, match, encode and decode strings are therefore of chief interest. Combinatorial problems about strings lie at the core of such algorithmic questions. Many such combinatorial problems are common in the string processing efforts in the different fields of application.

The purpose of this seminar is to bring together researchers from different disciplines whose interests are string processing algorithms and related combinatorial problems on words. The two main areas of interest for this seminar are Combinatorics on Words and Stringology. This report documents the program and the outcomes of Dagstuhl Seminar 14111 "Combinatorics and Algorithmics of Strings".

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1 Executive Summary

Maxime Crochemore James Currie Gregory Kucherov Dirk Nowotka

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Processing strings efficiently is of concern in practically every application field. Understanding the combinatorial properties of sequences is a prerequisite for designing efficient algorithms on them. The Dagstuhl seminar 14111 has been concerned with exactly that: *Combinatorics and Algorithmics of Strings*.



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Maxime Crochemore, James Currie, Gregory Kucherov, and Dirk Nowotka

This Dagstuhl seminar was attended by 41 researchers from 12 countries representing the two fields, algorithmics and combinatorics, about equally, although it needs to be mentioned that the overlap of these two communities is rather large. Inviting these close communities to Dagstuhl gave us the opportunity to start from substantial common ground and to work on scientific problems right from the beginning. Given that background, tutorials or other introductory sessions were not considered to be suitable elements for this seminar. Instead, much time was spent for problem posing and solving sessions. This seminar has clearly been research oriented.

The first seminar day, Monday, was entirely devoted to posing open problems. Based on those, the participants were able to form interest groups and engage into research activities early on. In the next days regular research talks and some more open problems were presented. However, time slots for research work were also allocated. On the last day of the seminar, Friday, we were able to already present some solutions to the problems posed in the beginning. In general, it is not to be expected that research problems are solved within a week (and most weren't), but it illustrates the impact of the meeting on catalysing research and collaboration between the participants.

The following two are great examples of such collaboration. Florin Manea asked about the complexity of deciding whether or not two words u and w are k-binomial equivalent, that is, is the number of occurrences of all scattered subwords up to length k equal in uand w? Contributions by Paweł Gawrychowski (polynomial Monte-Carlo algorithm in the logarithmic word-size RAM model), Juhani Karhumäki, and Wojciech Rytter (polynomial time on a unit-cost RAM model), and discussions with Dominik Freydenberger and Manfred Kufleitner finally led to the conclusion that the problem can be solved in polynomial time in the logarithmic word-size RAM model. Another problem was posed by Juhani Karhumäki and Michaël Rao (not present at the seminar) on the avoidability of shuffle squares. They asked: Does there exist an infinite word over some finite alphabet which avoids all factors that are a shuffle product of a word with itself? James Currie realized that shuffle squares can indeed be avoided applying the Lovász Local Lemma in his argument. However, this solution of avoidability in principle led to a proof for a very large alphabet, the size of which being a number of more than 40 digits. A few days after this Dagstuhl seminar Mike Müller improved that result by giving a rather low upper bound on the alphabet size of 10 on which shuffle squares can be avoided using a resent result by Joseph Miller. In general, it has to be noted that progress was made in many more areas and several papers in preparation were announced already.

Another notable highlight of the seminar was a session dedicated to word equations. Senior researchers of that particular research area, like Wojciech Plandowski and Volker Diekert, and young protagonists, like Aleksi Saarela, Štěpán Holub, and Artur Jeż, who talked about their recent efforts in developing the field, contributed and exchanged ideas. Such a unique assembly of major experts in word equations and their contributions at Dagstuhl was rather unique and a remarkable event.

In the light of such developments, it can be safely claimed that this seminar was a great success. Given the quality of presentations on this seminar and the constructive intensity of discussions, it is self-evident that a follow-up should be organised. We are grateful to all participants for their contributions to this successful seminar as well as to the staff of Schloss Dagstuhl for their great service.

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3 Overview of Talks, Open Problems, and Solutions
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3.1 Near Real-Time Suffix Tree Construction via the Fringe Marked Ancestor Problem

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 Joint work of Danny Breslauer; Giuseppe F. Italiano
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We contribute a further step towards the plausible *real-time* construction of suffix trees by presenting an on-line suffix tree algorithm that spends only $\mathcal{O}(\log \log n)$ time processing each input symbol and takes $\mathcal{O}(n \log \log n)$ time in total, where n is the length of the input text. Our results improve on a previously published algorithm that takes $\mathcal{O}(\log n)$ time per symbol and $\mathcal{O}(n \log n)$ time in total. The improvements are obtained by adapting Weiner's suffix tree construction algorithm to use a new data structure for the fringe marked ancestor problem, a special case of the nearest marked ancestor problem, which may be of independent interest.

3.2 Avoidability of Shuffle Squares

James D. Currie (University of Winnipeg, CA)

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A shuffle square is a word w such that for some word $v = \prod_{i=1}^{n} a_i = \prod_{i=1}^{n} b_i$ with $a_i, b_i \neq \epsilon$, $1 \leq i \leq n-1$, $a_n \neq \epsilon$, we can write

$$w = \prod_{i=1}^{n} (a_i b_i).$$

We then write $w \in v \sqcup v$. On the first day of the 2014 Dagstuhl seminar, *Combinatorics and Algorithmics of Strings*, J. Karhumäki asked the following question:

▶ Question 1. Are shuffle squares avoidable?

That is, whether for a large enough alphabet Σ , there is a word of Σ^{ω} in which no factor is a shuffle square. On the last day of the seminar, I pointed out that a very basic application of the Lovász Local Lemma gives avoidability.

▶ **Theorem 1.** Shuffle squares are k-avoidable, where $k = \lceil e^{95} \rceil$.

Evidently, it would be desirable to have a construction, and it remained to bring k down to some reasonable size. Much better bounds on the alphabet size (currently, k = 10) have been obtained by Mike Müller, cleverly using the criterion of Miller, recently promoted by Rampersad.

Probabilistic methods will also show that **shuffle powers** are avoidable. A shuffle *r*-power is a word $w \in x \sqcup p$ for some words x and p with p a prefix of x and $|xp|/|x| \ge r$.

The question of minimal alphabet sizes for avoidability remains open, and a construction is needed.

3.3 Hairpins and unambiguous context-free languages

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 Joint work of Volker Diekert; Steffen Kopecki; Victor Mitrana

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 languages in polynomial time," Information and Computation, 217:12–30, 2012.

 URL http://dx.doi.org/10.1016/j.ic.2012.04.003

In DNA computing one deals with strings over the bases A, C, G, and T. The Watson-Crick base pairing connects the bases A and T (resp. C and G) via hydrogen bonds; and the bases A and T (resp. C and G) are complementary. On an abstract level, $\{A, C, G, T\}$ forms a finite alphabet with *involution* Σ . That is for each $a \in \Sigma$ there is a unique $\overline{a} \in \Sigma$ such that $\overline{\overline{a}} = a$ for all a. In the case $\Sigma = \{A, C, G, T\}$ we have $\overline{A} = T$ and $\overline{C} = G$. A string of the form $\gamma \alpha \beta \overline{\alpha}$, where α is not too short (say $|\alpha| \geq 9$), may create a *hairpin* during annealing. This process may lead to elongation and denaturation; and new strings may occur as follows:



In an abstract setting, a hairpin completion transforms a string $\gamma \alpha \beta \overline{\alpha}$ into $\gamma \alpha \beta \overline{\alpha} \overline{\gamma}$ for $|\alpha| \geq \kappa$ where κ is some fixed small constant. This yields a transformation on formal languages:

$$L \mapsto H(L) = \{ \gamma \alpha \beta \overline{\alpha} \, \overline{\gamma} \in \Sigma^* \mid \gamma \alpha \beta \overline{\alpha} \in L \}.$$

There is also a more symmetric (and more interesting) variant

$$L \mapsto \{\gamma \alpha \beta \overline{\alpha} \,\overline{\gamma} \in \Sigma^* \mid \gamma \alpha \beta \overline{\alpha} \in L \lor \alpha \beta \overline{\alpha} \,\overline{\gamma} \in L\}.$$

However, for simplicity of the presentation it is enough to consider the case $L \mapsto H(L)$. The following two facts are known for regular languages $L \subseteq \Sigma^*$ by [1]:

- Given a DFA for L with n states, we can decide in time $\mathcal{O}(n^2)$ whether or not the hairpin completion H(L) is regular.
- If L is regular then H(L) is an unambiguous linear context-free language.

Analogous results hold also for the the symmetric variants, but proofs are much more demanding and complexities increase. This leads to the following two problems where the second one is motivated by our study of hairpin completions. Clearly, it has its interest in formal languages theory in its own right.

▶ Question 2. Is the following problem PSPACE-complete? The input is an NFA for L with n states. The question is whether or not the hairpin completion H(L) is regular.

▶ Question 3. Is the following problem decidable? The input is an unambiguous (linear) context-free grammar G. The question is whether the generated language L(G) is regular.

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A positive solution of the second problem would show that the decidability of the regularity for H(L) (for regular L) is merely a special case of a more general situation. There are many more interesting open problems about hairpin formations, for example it is not known whether or not regularity of the *iterated hairpin completion of a singleton language* is decidable. For the exact statement of the problem and related questions we refer to [1, 2].

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3.4 On The Minimum Number of Abelian Squares in a Word

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Gabriele Fici
Joint work of Gabriele Fici; Aleksi Saarela

An abelian square is a word that can be written as uv, where v is obtained from u by permuting letters (i.e., v is an anagram of u). Given an alphabet size k and an integer n, let $f_k(n)$ be the least number of abelian square factors that a word of length n over an alphabet of size k must contain. It is known that $f_k(n) = 0$ for every n if $k \ge 4$ [2], and it has been conjectured by Mäkelä in 1992 that $f_3(n) = 3$ for sufficiently large n, but this conjecture seems hard to prove¹. On the other side, it is easy to see that $f_1(n) = \lfloor n/2 \rfloor$. For the case k = 2, we have partial results supporting the conjecture that $f_2(n) = \lfloor n/4 \rfloor$. More details follow.

▶ **Definition 1.** A word w is Abelian Square Minimal (ASM) if no other word of the same length over the same alphabet contains less abelian squares than w.

▶ **Definition 2.** An abelian square of the form a^{2i} , for some letter *a* and integer i > 0, is called a trivial abelian square.

We have proved the following result:

▶ Lemma 3. Let w be a binary word of length n containing only trivial abelian squares. Then $|AS(w)| \ge \lfloor n/4 \rfloor$.

On the other hand, a sequence of binary words of length n containing only $\lfloor n/4 \rfloor$ distinct abelian squares is easy to show (take a word with only one b, placed in the middle). Hence, to prove that $f_2(n) = \lfloor n/4 \rfloor$, it is sufficient to prove the following:

▶ Conjecture 4. Let w be a binary ASM word of length |w| > 4. Then w contains only trivial abelian squares.

¹ Actually, Mäkelä asked if there exist arbitrarily large ternary words containing no abelian square of length greater than 2 [3]. Rampersad performed computer searches yielding words of length at least 3160 satisfying this condition [4].
Should the formula $f_2(n) = \lfloor n/4 \rfloor$ be true, we would have that a longest binary word containing only *n* abelian squares has length 4n + 3. More precisely, it would be the word $a^{2n+1}ba^{2n+1}$ or its complement $b^{2n+1}ab^{2n+1}$.

This is related to a conjecture of Fraenkel, Simpson and Paterson [1], who considered the minimum number of *inequivalent* abelian squares (that is, having different Parikh vectors) in a binary word:

▶ Conjecture 5. A longest word containing only n inequivalent abelian squares has length 4n + 3, and has one of the forms: $(ab)^{2n+1}a$, $a^{2n+1}ba^{2n+1}$ or their complements.

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3.5 On The Maximum Number of Abelian Squares in a Word

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An abelian square is a word that can be written as uv, where v is obtained from u by permuting letters (i.e., v is an anagram of u). Given a word w of length n, we investigate the maximum number of factors of w that are abelian squares. Contrarily to the case of ordinary squares, where this number is linear in n, it is easy to show that a word of length ncan contain $\Theta(n^2)$ many distinct abelian squares. Take for example $w_n = a^n b a^n b a^n$. For any $0 \le i, j \le n$, if the factor $a^i b a^n b a^j$ has even length, then it is an abelian square. Therefore, w_n contains $(n^2 + 3n + 1 + (-1)^n)/2$ many distinct abelian squares. This example motivates us to search for infinite words all factors of which contain a quadratic (in their length) number of distinct abelian squares.

▶ **Definition 1.** Let $as_w(n)$ denote the minimum number of distinct abelian squares in a factor of w of length n. An infinite word w is Abelian Square Rich if $as_w(n) = \Theta(n^2)$.

Together with Julien Cassaigne, we proved that the Thue-Morse word (that is the fixed point of the substitution $\mu : 0 \mapsto 01, 1 \mapsto 10$) is Abelian Square Rich.

We raise the following question:

▶ Question 4. Is every Sturmian word Abelian Square Rich?

First, we can prove that a factor of a Sturmian word is an abelian square (resp. an abelian k-power) if and only if both of its Parikh vector components are divisible by 2 (resp. by k). Then, using standard techniques of Number Theory based on results of approximation of irrationals by rationals, we can prove that the number of factors of length n of a Sturmian word s that are abelian squares is, on average, linear in n. This implies the following result:

▶ **Theorem 2.** Let *s* be a Sturmian word. If *s* is *k*-power free for some $k \in \mathbb{R}^+$, then *s* is Abelian Square Rich.

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For example, the Fibonacci word (that is the fixed point of the substitution $\phi : 0 \mapsto 01, 1 \mapsto 0$) is $\frac{5+\sqrt{5}}{2}$ -power free, and therefore is Abelian Square Rich.

A slight different point of view consists in considering two abelian squares inequivalent if they have different Parikh vectors, and not simply if they are different words [1]. Sturmian words only have a linear number of inequivalent abelian squares, since they have abelian complexity equal to 2 for every n > 0. Nevertheless, computations support the following conjecture (also proposed by W. Rytter [2]).

▶ Conjecture 3. A word of length n contains $O(n\sqrt{n})$ many inequivalent abelian squares.

We propose the following open problem:

▶ Question 5. Let $ias_w(n)$ denote the minimum number of distinct inequivalent abelian squares in a factor of w of length n. Does an infinite word w exist such that $ias_w(n) = \Theta(n\sqrt{n})$?

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3.6 Are there better measures of compressibility than Empirical Entropy?

Johannes Fischer (TU Dortmund, DE)

Empirical entropy as a complexity measure is widely used in the analysis of data structures and algorithms, although it does not capture very common types of text regularities. We ask what one should expect from a better measure of compressibility, and propose a measure based on longest common prefixes.

3.7 Two open problems on pattern languages

Dominik D. Freydenberger (Goethe-Universität Frankfurt am Main, DE)

A pattern is a word $\alpha \in (\Sigma \cup X)^+$, where Σ and X are disjoint alphabets (of terminals and variables, respectively). A pattern α generates the language

$$L_{\text{NE},\Sigma}(\alpha) := \{\sigma(\alpha) \mid \sigma \text{ is a substitution}\},\$$

where a substitution is a morphism $\sigma : (\Sigma \cup X)^+ \to \Sigma^+$ with $\sigma(a) = a$ for all $a \in \Sigma$.

3.7.1 Degrees of ambiguity

For every pattern α and every word $w \in L_{\text{NE},\Sigma}(\alpha)$, the degree of ambiguity of w (w. r. t. α) is the number of distinct substitutions σ with $\sigma(\alpha) = w$. The degree of ambiguity of α is the maximal degree of ambiguity of any word $w \in L_{NE,\Sigma}(\alpha)$. As shown by Mateescu and Salomaa [1], for every $k = 2^m 3^n$ $(m, n \ge 0)$, a pattern with degree of ambiguity k can be effectively constructed. For all other finite degrees of ambiguity, even the existence of such patterns is unknown:

 \blacktriangleright Question 6. Are there patterns with degree of ambiguity k such that k is not of the form $k = 2^m 3^n \ (m, n \ge 0)$?

3.7.2 Inclusion depth

For a pattern α , we define its *inclusion depth* $\mathrm{ID}_{\Sigma}(\alpha)$ as the largest n for which there exist patterns $\beta_1, \ldots, \beta_{n-1}$ with

 $\Sigma^+ \supset L_{\text{NE},\Sigma}(\beta_1) \supset \cdots \supset L_{\text{NE},\Sigma}(\beta_{n-1}) \supset L_{\text{NE},\Sigma}(\alpha).$

By definition, $ID_{\Sigma}(\alpha)$ is always finite, and Luo [2] gives the lower bound $ID_{\Sigma}(\alpha) \geq 2|\alpha|$ $|\operatorname{var}(\alpha)| - 1$, where $\operatorname{var}(\alpha)$ is the set of variables in α . Apart from this, little is known about $ID_{\Sigma}(\alpha)$. In particular, the following question is open:

▶ Question 7. Given a pattern α , can we compute $ID_{\Sigma}(\alpha)$?

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3.8 **Decomposition to palindromes**

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Joint work of Anna Frid; Svetlana Puzynina; Luca Q. Zamboni

Main reference A.E. Frid, S. Puzynina, L.Q. Zamboni, "On palindromic factorization of words," Advances in

Applied Mathematics 50:737-748, 2013. URL http://dx.doi.org/10.1016/j.aam.2013.01.002

Given a non-periodic infinite word, is it true that for each k it contains a factor (version: a prefix) which cannot be decomposed as a concatenation of at most k palindromes? In a 2013 paper with S. Puzynina and L. Zamboni, we have proved this conjecture for the case of overlap-free words and for a wider class containing in particular the Sierpinski word. However, the general case remains open, and moreover, there is no proof even for general Sturmian words.

3.9 Order-preserving pattern matching with k mismatches

Paweł Gawrychowski (MPI für Informatik – Saarbrücken, DE)

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Joint work of	Paweł Gawrychowski; Przemysław Uznanski
Main reference	P. Gawrychowski, P. Uznanski, "Order-preserving pattern matching with k mismatches," in Proc.
	of the 25th Annual Symp. on Combinatorial Pattern Matching (CPM'14), to appear; pre-print
	available as arXiv:1309.6453v2 [cs.DS].
URL	http://arxiv.org/abs/1309.6453v2

We study a generalisation of the recently introduced order-preserving pattern matching, where instead of looking for an exact copy of the pattern, we only require that the relative order between the elements is the same. In our variant, we additionally allow up to k mismatches between the pattern and the text, and the goal is to construct an efficient algorithm for small values of k. For a pattern of length m and a text of length n, our algorithm detects an order-preserving occurrence with up to k mismatches in $\mathcal{O}(n(\log \log m + k \log \log k))$ time.

3.10 Algebraic properties of word equations

Štěpán Holub (Charles University – Prague, CZ)

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    Joint work of Štěpán Holub; Jan Žemlička
    Main reference Š. Holub, J. Žemlička, "Algebraic properties of word equations," arXiv:1403.1951v1 [cs.FL], 2014.
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In [1], Aleksi Saarela has introduced a new approach to word equations that is based on linear-algebraic properties of polynomials encoding the equations and their solutions. We develop further this approach and take into account other algebraic properties of polynomials, namely their factorization.

It turns out, that a special factor of Saarela's determinant corresponds to each length type of a solution. This, in particular, allows to improve the bound for the number of independent equations with minimal defect effect from quadratic to linear.

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3.11 Local Recompression for Word Equations

Artur Jeż (MPI für Informatik – Saarbrücken, DE)

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Main reference A. Jeż, "Recompression: a simple and powerful technique for word equations," in Proc. of the 30th Int'l Symp. on Theoretical Aspects of Computer Science (STACS'13), LIPIcs, Vol. 20, pp. 233–244, 2013.

URL http://dx.doi.org/10.4230/LIPIcs.STACS.2013.233

In this talk I will present an application of a simple technique of local recompression to word equations. The technique is based on local modification of variables (replacing X by aX or Xa) and iterative replacement of pairs of letters occurring in the equation by a 'fresh' letter,

which can be seen as a bottom-up compression of the solution of the given word equation, to be more specific, building an SLP (Straight-Line Programme) for the solution of the word equation. Using this technique we give a new, independent and self-contained proofs of many known results for word equations. To be more specific, the presented (nondeterministic) algorithm runs in $\mathcal{O}(n \log n)$ space and in time polynomial in n and $\log N$, where n is the size of the input equation and N the size of the length-minimal solution of the word equation.

The obtained algorithm is easy to explain and generalises to many extension of word equations: free monoids with involution, free groups, context unification.

3.12 String Range Matching

Juha Kärkkäinen (University of Helsinki, FI)

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 Joint work of Juha Kärkkäinen; Dominik Kempa; Simon J. Puglisi
 Main reference J. Kärkkäinen, D. Kempa, S. J. Puglisi, "String Range Matching," in Proc. of the 25th Annual Symp. on Combinatorial Pattern Matching (CPM'14), to appear.

Given strings X and Y the exact string matching problem is to find the occurrences of Y as a substring of X. An alternative formulation asks for the lexicographically consecutive set of suffixes of X that begin with Y. We introduce a generalisation called string range matching where we want to find the suffixes of X that are in an arbitrary lexicographical range bounded by two strings Y and Z. The problem has applications in distributed suffix sorting, where Y and Z are themselves suffixes of X.

Exact string matching can be solved in linear time using constant extra space. The open question is:

▶ Question 8. What is the time-space complexity of string range matching?

We have described algorithms for string range matching that have an extra logarithmic factor in either the time or the space [CPM 2014].

▶ Question 9. Are there algorithms with a better time-space complexity? Or can one show that string range matching cannot be solved in linear time and constant extra space?

3.13 Sum of Digits of n and n^2

Steffen Kopecki (University of Western Ontario – London, CA)

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 Joint work of Steffen Kopecki; Thomas Stoll
 Main reference K. G. Hare, S. Laishram, T. Stoll, "The sum of digits of n and n²," International Journal of Number Theory, 07(7):1737–1752, 2011.
 URL http://dx.doi.org/10.1142/S1793042111004319

I am presenting a problem that has been presented on last year's workshop *Challenges in Combinatorics on Words* at the Fields Institute by Thomas Stoll. Since last year we made some progress in solving the problem, but despite our efforts there are still some cases left open.

For $n \in \mathbb{N}$, let $s_2(n)$ denote the sum of digits in the binary expansion of n. In other words, if $s_2(n) = k$, then n can be written as $n = 2^{r_0} + 2^{r_1} + \cdots + 2^{r_{k-1}}$ for integers

 $0 \le r_0 < r_1 < \cdots < r_{k-1}$. For $k \in \mathbb{N}$, we are investigating the set of positive odd integers n which satisfy the equation $s_2(n) = s_2(n^2) = k$. We let

$$S_k = \{n \text{ odd } | s_2(n) = s_2(n^2) = k\}$$

and ask the question for which numbers $k \in \mathbb{N}$ the set S_k is infinite. Our investigation is restricted to odd numbers because for every odd number n which satisfies the equation, there is an infinite family of even numbers $\{n \cdot 2^i \mid i > 0\}$ which satisfy the equation as well.

From [1] we obtain that

- for $k = 1, \ldots, 8$ the set S_k is finite, and
- for k = 12, 13 and $k \ge 16$ the set S_k is infinite.

Furthermore, since last year's workshop, we could prove that

for k = 9, 10 the set S_k is finite.

▶ Question 10. Is the set S_k finite or infinite for k = 11, 14, 15.

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3.14 The Burrows-Wheeler Transform with Permutations

Manfred Kufleitner (Universität Stuttgart, DE)

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We present a new variant of the Burrows-Wheeler Transform (BWT). It involves an action of a group G on an ordered alphabet Σ . We write a^g for the letter obtained by applying the element $g \in G$ to $a \in \Sigma$. For $u = a_1 \cdots a_n$ we let $u^g = a_1^g \cdots a_n^g$ be the homomorphic extension to words $u \in \Sigma^*$. Let \tilde{u} denote the lexicographically minimal element in $\{u^g \mid g \in G\}$. Let $(\tilde{v}_1, \ldots, \tilde{v}_n)$ be the sorted list of the conjugates v_i of u. The BWT with permutations (BWTP) of u is BWTP_G(u) = (w, i, g) where w is the sequence of the last letters in the sorted list of the words \tilde{v}_i , the number i is an index with $\tilde{u} = \tilde{v}_i$, and $g \in G$ satisfies $\tilde{u} = u^g$. It is easy to show that BWTP is injective. It would be desirable to find efficient algorithms for computing the BWTP and its inverse. Moreover, for some fixed compression algorithm, it would be interesting to identify the groups G such that BWTP_G(u) compresses best; this could help in revealing hidden symmetries of u.

3.15 Text Indexing: Easy and Difficult

Moshe Lewenstein (Bar-Ilan University – Haifa, IL)

Text indexing refers to the problem of preprocessing a text for future queries. The goal is to construct a data structure quickly in minimum space in order to answer queries quickly.

Maxime Crochemore, James Currie, Gregory Kucherov, and Dirk Nowotka

For exact match queries data structures, such as suffix trees, suffix arrays, and others, are well known to be constructible in linear time and space for later linear (pattern length) queries.

We first show several examples where this is still the case for extended query definitions. We then show an interesting separation between the definition of sum-queries and productqueries. For small constant sized alphabet $1, \ldots, c$ sum-queries is solvable efficiently. On the other hand, we show that product-queries, under the 3SUM-Hardness assumption, need either $\mathcal{O}(n^2)$ preprocessing time or $\mathcal{O}(n)$ query time.

This has consequences for the problem of histogram (or jumbled) indexing which has garnered much interest lately.

3.16 Testing *k*-binomial equivalence

Florin Manea (Universität Kiel, DE)

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 Joint work of Dominik Freydenberger; Paweł Gawrychowski; Juhani Karhumäki; Manfred Kufleitner; Florin Manea; Wojciech Rytter

The binomial coefficient of two words u and v is the number of times v occurs as a scattered factor of u, and it is denoted as $\binom{u}{v}$. Two words u and w over an alphabet Σ are k-binomial equivalent if $\binom{u}{v} = \binom{w}{v}$ for all words $v \in \Sigma^{\leq k}$. In this setting, it seems interesting to show that one can decide in polynomial time for a pair of words u and w and a number k whether u and w are k-binomial equivalent. As a first result, Paweł Gawrychowski showed that the problem can be solved efficiently by a polynomial Monte-Carlo algorithm in the logarithmic word-size RAM model. Then, Juhani Karhumäki and Wojciech Rytter noted that the problem can be reduced at the problem of testing whether two nondeterministic finite automata without λ -transitions are path equivalent. It is known that this problem can be solved in polynomial time on a unit-cost RAM model. Further discussions involving Dominik Freydenberger and Manfred Kufleitner led to a final solution of this problem, concluding that in fact the problem can be solved in polynomial time in the logarithmic word-size RAM model. As an open problem, we ask the following:

▶ Question 11. What is the complexity of finding, for two words w and u and a number k all the factors of w that are k-binomial equivalent to u. Can this problem be solved more efficiently than just checking whether each factor of w is k-binomial equivalent to u?

3.17 *k*-Abelian Pattern Matching

Robert Mercaş (Universität Kiel, DE)

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Joint work of Thorsten Ehlers; Florin Manea; Robert Mercaş; Dirk Nowotka Main reference T. Ehlers, F. Manea, R. Mercaş, D. Nowotka, "k-Abelian Pattern Matching," in Proc. of the 18th Int'l Conf. on Developments in Language Theory (DLT'14), to appear.

Two words are called k-abelian equivalent, if they share the same multiplicities for all factors of length at most k. We present an optimal linear time algorithm for identifying all occurrences of factors in a text that are k-abelian equivalent to some pattern P. Moreover,

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an optimal algorithm for finding the largest k for which two words are k-abelian equivalent is given. The complexity of algorithms for online versions of the k-abelian pattern matching problem is also considered. In particular we show results regarding the investigation of the pattern matching problem for k-abelian equivalences in the setting of online algorithms, and propose a series of real-time solutions of this problem. One of the questions we propose is to:

▶ Question 12. Identify an optimal linear time complexity algorithm for the pattern matching problem for k-abelian equivalences.

We also show results for an extended form of k-abelian equivalence.

3.18 Bell numbers modulo 8

Eric Rowland (University of Liège, BE)

The *n*th Bell number B(n) is the number of partitions of an *n*-element set. The sequence $B(n)_{n\geq 0}$ is $1, 1, 2, 5, 15, 52, 203, 877, \ldots$

▶ Question 13. Is it true that B(n) is not divisible by 8 for all $n \ge 0$?

Experiments suggest that $(B(n) \mod 8)_{n\geq 0}$ is a 2-automatic sequence, meaning that there is a deterministic finite automaton with output that outputs $B(n) \mod 8$ when fed the standard base-2 representation of n. Recently, Yassawi and I [2] showed how to automatically compute automata for many sequences modulo prime powers, thereby giving such congruences purely mechanically. However, the sequence of Bell numbers appears to not be accessible by this method.

During the workshop, Mike Müller found a paper of Lunnon, Pleasants, and Stephens [1] which shows that $(B(n) \mod p^{\alpha})_{n\geq 0}$ is in fact periodic. Modulo 8, the sequence of Bell numbers has period 24. Computing the first 24 terms then gives a proof that no Bell number is divisible by 8. Also, no Bell number is congruent to 6 modulo 8. A comment in the OEIS entry for the Bell numbers, https://oeis.org/A000110, referencing the Lunnon-Pleasants-Stephens paper has been clarified with the proper theorem. Steffen Kopecki found an independent proof, using a Pascal-like triangle for the Bell numbers.

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3.19 Maximum Number of Distinct and Nonequivalent Nonstandard Squares in a Word

Wojciech Rytter (University of Warsaw, PL)

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 Joint work of Tomasz Kociumaka; Jakub Radoszewski; Wojciech Rytter; Tomasz Waleń
 Main reference T. Kociumaka, J. Radoszewski, W. Rytter, T. Waleń, "Maximum Number of Distinct and Nonequivalent Nonstandard Squares in a Word," in Proc. of the 18th Int'l Conf. on Developments in Language Theory (DLT'14), to appear.

The combinatorics of squares in a word depends on how the equivalence of halves of the square is defined. We consider Abelian squares, parameterized and order-preserving squares. The word uv is an Abelian (parameterized, order-preserving) square if u and v are equivalent in the Abelian (parameterized, order-preserving) sense. The maximum number of ordinary squares is known to be asymptotically linear, but the exact bound is still investigated.

We present several results on the maximum number of distinct squares for nonstandard subword equivalence relations. Let $SQ_{Abel}(n,k)$ and $SQ'_{Abel}(n,k)$ denote the maximum number of Abelian squares in a word of length n over alphabet of size k, which are distinct as words and which are nonequivalent in the Abelian sense, respectively.

We prove that

$$SQ_{Abel}(n,2) = \Theta(n^2), \quad SQ'_{Abel}(n,2) = \Omega(n^{1.5}/\log n)$$

We also give linear bounds for parameterized and order-preserving squares for small alphabets:

$$SQ_{param}(n,2) = \Theta(n), \quad SQ_{op}(n,O(1)) = \Theta(n).$$

As a side result we construct infinite words over the smallest alphabet which avoid nontrivial order-preserving squares and nontrivial parameterized cubes (nontrivial parameterized squares cannot be avoided in an infinite word).

3.20 Parametric solutions of word equations

Aleksi Saarela (University of Turku, FI)

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By Hmelevskii's theorem [1], every constant-free word equation on three unknowns has a parametric solution. In [3], an exponential upper bound was proved for the length of such a parametric solution.

▶ Question 14. How many parametric formulas do we need in such a solution, at most?

The best known lower bound for the number of formulas is three: The equation xyxzyz = zxzyxy has a parametric solution

 $(x,y,z)=(p,q,\varepsilon), \qquad (x,y,z)=(p,q,pq), \qquad (x,y,z)=(p^i,p^j,p^k),$

but it can be proved that it does not have a parametric solution with just two formulas. As another example, consider the equation $xy = z^n$. It has a parametric solution with $\lceil n/2 \rceil$ formulas, but it is not known whether this is optimal.

The above-mentioned equation xyxzyz = zxzyxy is also related to the following big open problem:

▶ Question 15. How long sequences E_1, \ldots, E_n of non-trivial word equations on three unknowns do we have such that the systems E_1, \ldots, E_i $(i = 1, \ldots, n)$ are pairwise non-equivalent and have non-periodic solutions?

The best known example is the sequence xyz = zxy, xyxzyz = zxzyxy, xz = zx. For more information, see [2].

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3.21 Efficient generation of repetition-free words

Arseny M. Shur (Ural Federal University – Ekaterinburg, RU)

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When some repetition is proved to be avoidable over some alphabet, we usually get an explicit construction of infinite repetition-free words. Normally, such constructions are based on substitutions satisfying certain restrictions (in the simplest case, just on morphisms). As a result, the obtained words have some "additional" properties, like ultimate recurrence, which do not follow from repetition-freeness. Hence it is quite useful to have a generator which can produce any word from a given repetition-free language. Such generators can rely on the general "local resampling" idea used by Moser and Tardos for the constructive proof of the Lovasz Local Lemma [2].

An algorithm for square-like repetitions was first proposed by Grytczuk, Kozik, and Witkowski [1] and reformulated for squares by Rampersad. We modified this algorithm to convert random words over $\Sigma_k = \{1, \ldots, k\}$ to square-free words over Σ_{k+1} ; this can be done more efficiently than the conversion over the same alphabet. Without falling into implementation details, our algorithm works as follows. On each step, one letter is appended to the right end of the square-free word under construction. If the resulting word ends with a square, then the right half of this square is dismissed, otherwise we just proceed to the next step. To get the letter for appending, we take a random letter over Σ_k , say *i*, sort the letters of Σ_{k+1} by the recency of their last occurrence in the square-free word, and take the (i+1)th element of the sorted list.

We proved the following

▶ **Theorem 1.** The expected number of random k-ary letters used by the above algorithm to construct a (k+1)-ary square-free word of length n is

$$N = n(1 + 2/k^2 + 1/k^3 + 4/k^4 + \mathcal{O}(1/k^5)) + \mathcal{O}(1).$$

Thus, if k is not small, then the algorithm converts random words to square-free words of nearly the same length. However, for the extremal case of ternary square-free words we have

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no theoretical bound on the conversion rate. From experiments we learned that the expected value of N is linear in n in this case and, moreover, $N \approx 12.5n$. The following problems naturally develop the obtained results.

▶ Question 16. Give an upper bound on the conversion ratio of the above algorithm for the case of ternary square-free words.

▶ Question 17. Give efficient algorithms generating cube-free words; words, avoiding fractional powers; Abelian square-free words.

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Report from Dagstuhl Perspectives Workshop 14112

Massively Open Online Courses, Current State and Perspectives

Edited by

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— Abstract

The Perspectives Workshop on "Massively Open Online Courses, Current State and Perspectives" took place at Schloss Dagstuhl on March 10–13, 2014. Twenty-three leading researchers and practitioners from informatics and pedagogical sciences presented and discussed current experiences and future directions, challenges, and visions for the influence of MOOCs on university teaching and learning. The first day of the workshop consisted of a series of presentations in which each participant presented those topics and developments he or she considered most relevant for the future development of MOOCs. The abstracts of these talks are given in the first part of this report. On the second and third day the participants divided into several working groups according to the main thematic areas that had been identified on the first day. This gives rise to a *Manifesto* to be published in the Dagstuhl Manifesto series and to identifying main research questions rised by the emergence of MOOCs: they are summarized in the second part of this report.

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1 Executive Summary

Pierre Dillenbourg Claude Kirchner John C. Mitchell Martin Wirsing

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Online education is not new; Massively Open Online Courses (MOOCs) are. Their uniquely powerful combination of classical digital teaching tools (videos, audios, graphics or slides), individualized tools for acquiring and validating knowledge, and appropriate use of dedicated social networks makes them a new and formidable means of accessing knowledge and education. If backed up with scientific and pedagogical excellence, MOOCs allow one to reach and teach simultaneously tens of thousands and even hundreds of thousand of learners in a new pedagogical dynamic.



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Massively Open Online Courses, Current State and Perspectives, *Dagstuhl Reports*, Vol. 4, Issue 3, pp. 47–61 Editors: Pierre Dillenbourg, Claude Kirchner, John C. Mitchell, and Martin Wirsing DAGSTUHL Dagstuhl Reports

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Of the numerous MOOCs initiatives that have recently emerged, especially in the US and Europe, a few seem to be surfacing with an extremely important impact. This creates a very new situation and indeed can be considered as the informatics community's first main impact on knowledge dissemination and teaching. MOOCs will very likely induce a radical change in teaching mechanisms and their links to the economic and production systems. The consequences with respect to the transmission of culture and educational content, and on society as a whole, will be deep.

This situation raises many questions in a range of different disciplines with respect to ethics, intellectual properties, and data protection and privacy, necessitating an in-depth understanding of the current state of affairs and future trends in these research areas.

This Dagstuhl Perspectives Workshop brought together leading researchers and practitioners working in or on MOOCs initiatives in order to provide a forum for discussing participants' current experiences and initial feedback. Scientists from several key disciplines, including informatics, pedagogy, economy, psychology and sociology, have meet to discuss the current state of the situation and envision the next steps. In particular, they have addressed questions relative to current research on the pedagogical engineering of MOOCs, economical models, ethical issues, the technical development of platforms, and sharing.

The first day of the workshop consisted of a series of presentations in which each participant presented those topics and developments he or she considered most relevant for the future development of MOOCs. On the second and third day the participants divided into several working groups according to the main thematic areas that had been identified on the first day.

From the working groups outcomes, a Manifesto has been worked out and will appear in the *Dagstuhl Manifestos Collection*.

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3.1 Crowdlearning

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François Bry (LMU München, DE)

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This presentation reports on on going work at the University of Munich and the Saarland University on novel eLearning systems combining social learning, direct instruction, and enquiry-based learning.

A first system Backstage, deployed since 2012, is presented. Backstage is targeted at an immediate feedback and interactions in large class lectures.

The project Crowdlearning aims at going beyond Backstage by offering a platform for both class-learning and self-learning, learning Analytics for an immediate feedback to both learners and teachers, and building upon human computation peer teaching, peer marking, and teachers' collaboration.

3.2 Looking for New Efficient & Effective Educational Bundles

Carlos Delgado Kloos (Universidad Carlos III de Madrid, ES)

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Carlos Delgado Kloos

In the industrial age, mass production was achieved by division of labour, synchronicity, and strict rules. When the Prussian education system was introduced 2 centuries ago making education compulsory, the same principles were used to achieve efficiency in education by dividing students by age, ideas into subjects, and days into periods. In an age where access to (rapidly changing) information is pervasive, new skills have to be taught, and technology allows new ways of interaction, the challenge is to find new structures that provide education in an efficient and effective way. In the second part of my talk, I report about three initiatives at Universidad Carlos III de Madrid of using MOOC-like technology and content in residential courses that complement our activity around MOOCs (in MiríadaX and edX). A number of different platforms have been used (Khan Academy platform, Google Course Builder, and open edX) for different purposes (review courses, SPOCs as a complement to residential courses, and reinforcement content for failing students). All these experiments intend to use MOOC-technology for removing inefficiencies in on-campus education, and finding new structures and models to improve residential education.

3.3 Design for scalability: Reflections on trade-offs in MOOCs

Yannis Dimitriadis (University of Valladolid, ES)

Lesson learnt from the study of scalability in telematics may be useful for on-line education, such as the case of MOOCs. This position paper suggests the use of the "design for learning" approach in order to study the effects and trade-offs of scalability in MOOCs

3.4 MOOC? Inverted Classroom! Some initial Experience with an esruoC in computer science

Jens Dittrich (Universität des Saarlandes, DE)

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 Main reference J. Dittrich, "Die Umgedrehte Vorlesung – Chancen f
 ür die Informatiklehre," Datenbank-Spektrum, 14(1):69–76, 2014.
 URL http://doi.org/10.1007/s13222-013-0143-9

In this talk I explain my experience with a flipped (aka inverted) university lecture in computer science. The experience was mostly positive. I describe things that worked and that did not work. In additon, I give recommendations on how to address minor things that did not work in future lectures.

3.5 Designing a research policy on MOOCs (preliminary investigations)

Gilles Dowek (INRIA – Paris, FR)

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New research problems emerge to design better courses and better platforms. MOOCs platforms are a measuring instrument for research in pedagogy.

3.6 Supporting Campus in the Cloud, Course Customization, and Instructional and Student Communities

Douglas H. Fisher (Vanderbilt University, US)

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© Douglas H. Fisher Main reference D. O. Bruff, D. H. Fisher, K. E. McEwen, B. E. Smith, "Wrapping a MOOC: Student Perceptions of an Experiment in Blended Learning," MERLOT Journal of Online Learning and Teaching, 9(2), June 2013.

 ${\tt URL \ http://jolt.merlot.org/vol9no2/bruff_0613.htm}$

I will summarize my experience with blended learning models that use MOOC material by other faculty, as well as material I have produced myself; followed by general observations about the implications of MOO Education (MOOE) for on-campus education, thematic and regional learning and teaching communities, and instructional collaborations that cross institutional boundaries.

3.7 Virchow-Villermé, a French-German experience on MOOCs in the field of Global Public Health

Antoine Flahault (Paris Descartes University, FR)

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 URL https://www.france-universite-numerique-MOOC.fr/courses/VirchowVillerme/05001/Trimestre_1_2014/about?xtor=AL-3

This presentation will present an attempt of setting up a series of MOOCs in the field of global health and public health on a non US platform (France Université Numérique on Open-edX). A road map has been defined from an international consultation of experts, health professionals and students, leading to a selection of 70 MOOCs which were considered as expected to be proposed on a platform dedicated to public and global health. Four MOOCs are currently launched, and this first experience will be discussed. Questions on options for the economic model will be raised, and issues relative to confidentiality of students' data.

3.8 SPOCs Can Help Refactor Residential Course Offerings

Armando Fox (University of California – Berkeley, US)

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- 1. The current "one size fits all" model of residential course delivery is a poor fit for exploding enrollments as well as for faculty productivity in an era of tightening budgets.
- 2. Separating the scalable from the non-scalable parts of a course allows the two to be resourced separately. The scalable parts can serve the mass of the distribution while the non-scalable parts can be resourced in a way more tailored to utilizing the outliers, both the superstars and the stragglers.
- 3. MOOC technology in the form of curated SPOCs, with appropriate new teaching roles supporting the course, can play a role in both the scalable and non-scalable elements.

3.9 Open Linked Data and Models for MOOCs

Serge Garlatti (Telecom Bretagne – Brest, FR)

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This position paper presents a MOOC toolkit for Inquiry-based Learning (called iMOOCs) or connectivism (called cMOOCs) approaches with peer assessments for learning. A toolkit, called SMOOPLE (Semantic Massive Open Pervasive Learning Environment), has been designed to support such type of learning. It consists in a set of social media tools used for producing and collecting content and communicate with peers, dashboards and semantic services. The explicit models (defined as ontologies: stakeholders, learning activity, peer assessment, etc.) were designed to support learning (a guide for learners and for monitoring, scaffolding, common language, etc.) and to annotate produced information. By means of Linked data, all information from social media tools and user interaction with dashboards can be linked to provide support and relevant information to the different stakeholders. Finally, some perspectives are pointed out.

3.10 MOOCs @ Institut Mines-Télécom

Serge Garlatti (Telecom Bretagne – Brest, FR)

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This position paper presents the main goals of Institut Mines Telecom (IMT) for MOOCs development. IMT plan to develop a catalog of MOOCs, around 10 per year, to be innovative in MOOCs and to integrate MOOCs in its training offer, that is to say sharing courses between IMT schools and enabling an ambitious, lifelong, training offer.

3.11 Analysis of attrition curves from 39 MOOCs (from Stanford) and what this says about student engagement

David Glance (The University of Western Australia - Crawley, AU)

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In their current instantiation, Massive Open Online Courses (MOOCs) represent a form of educational delivery with little or no barrier to entry. In part due to the extreme ease of enrolling, low completion rates have been a notable characteristic of MOOCs with as few as 5–10% of students who enrolled gaining a certificate of completion. Beyond these observations, little is known about the patterns of attrition, nor how they may vary amongst different groups of MOOC participants.

Activity data was analysed from log records collected from 48 MOOCs run by Stanford University between 2011 and 2013 on Coursera. There were 23 unique courses, some of which were repeated. A novel analysis was devised and applied to the data which showed that attrition varies little between at least two different groups of MOOC participants, those that audited the course and those that actively participated in assessments.

The results indicate that attrition is not influenced by levels of participation in a MOOC and attrition is further not influenced by attributes of the course.

3.12 Learning groups in xMOOCs: Potential and Pitfalls

Jörg M. Haake (FernUniversität in Hagen, DE)

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In this talk, it is explored whether and how positive experience with learning groups in Distance Learning courses could be mapped on xMOOCs. Issues and solutions for the different phases of group learning are presented, and results from a study of the effect of CSCL scripts on semester-long learning groups are briefly reported. Pitfalls/problems and solution ideas for applying learning groups in an xMOOC are discussed.

3.13 MOOC enrolments: searching for meaning in large numbers

Jeff Haywood (University of Edinburgh, GB)

This presentation explores the features of the learners enrolled on University of Edinburgh MOOCs in their first few iterations on the Coursera platform. Age, prior educational experience, intentions for study, choice of MOOC etc are compared between different MOOCs and different iterations.

The demographics of the learners and their reasons for studying the MOOC on which they had enrolled were collected in an online pre-MOOC survey. There were 50k completed surveys in January 2013 and 45k completed surveys in the same MOOCs re-run at various times up to March 2014 (approx. 25% of enrolments).

The learners enrolled on later offerings of each MOOC were quite similar in age, gender, location and prior educational level to those on the first offering, which had been at a time when MOOCs were quite a new phenomenon, suggesting some stability in their different audiences. Despite their high educational levels (most had Bachelor or Masters degrees), learners were taking MOOCs in new subjects and not re-studying in the same subject as their qualifications. Younger learners were much more interested in certificates and MOOCs as support for their careers than were the (majority) older learners, but all were interested to learn new things, and many were interested in experiencing online learning, a key skill for the future. MOOC learners in the later course offerings were twice as likely to have already studied on a MOOC than in the first offerings, suggesting that these are increasingly repeat learners, and hence more like lifelong learners ('extension') than traditional students.

The Edinburgh data report can be found at https://www.era.lib.ed.ac.uk/handle/1842/6683.

3.14 Learning Analytics Techniques targeting Resource Usage in Online Courses

Heinz Ulrich Hoppe (Universität Duisburg-Essen, DE)

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MOOCs (but also other types of online courses) make intensive use of a variety learning resources provided online, including video clips, quizzes, but also student-generated content. This talk will present specific analysis techniques related to usage patterns around such resources. Our method relies essentially on a generalization of the clique percolation method for subcommunity detection to bi-partite student-artefact networks. In particular we uncover bipartite clusters of students and resources in those networks and propose a method to identify patterns and traces of their evolution over time. The approach is exemplified with a blended learning course on "Interactive Teaching and Learning Environments".

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3.15 Inria for FUN

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Claude Kirchner (Inria - Paris, FR)

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Claude Kirchner

The profound digital revolution transforming our society is now fully impacting education.

The emergence of MOOCs is a strategical issue as it impacts knowledge transfert, pedagogy as well as the relationship between all the users of the educative systems. A much in depth individual and collective knowledge of the students behaviors, competences and abilities results from these new tools.

In this context and since two of its missions are research and knowledge transfert, Inria has created its MOOC Lab with four missions:

- 1. Provide a high scientific, pedagogical and ethical qualities platform alternative;
- 2. Develop contents, in particular in informatics and mathematics domains;
- 3. Help in the development of research;
- 4. Adapt and experiment the platform with new ideas and contents. To fullfil these objectives, Inria decided to use and adapt the openEdX software.

Because of its strategic importance and in order to help, share and mutualize the elaboration of MOOCs as well as their availability, the French ministry of higher education and research launched FUN (France Université Numérique) and in this context asked Inria to help setting up its MOOC platform. So Inria's MOOC Lab customized the openEdX software to adapt it to the French and FUN contexts, in collaboration with CINES (academic computing center) and Renater (association in charge of the French academic network). The platform has been opened in October 2013 for students registration and the first courses stated in January 2014. Beginning of March, there are more than 200 000 registered students to the 32 available courses.

Inria's MOOC Lab is now continuing to work on the software as well as contributing to develop multilingual contents and organizing research seminar on MOOC related topics in relationship with many universities and research centers locally and internationally.

This talk will present a short overview of these activities.

3.16 Observing an open learning process: a modeled trace oriented framework

Alain Mille (University Claude Bernard – Lyon, FR)

After introducing the concept of observational semantics, a general framework to trace an open learning process will be detailed: listening the logs on the platform server, collecting chosen information on the learner browser, giving control of the tracing process to the learner, etc. The approach will be illustrated on a concrete example (a MOOC in Lyon). Further readings, bibliography and useful URL to contribute to the platform will be provided. It should be possible to make demos on line during the breaks.

3.17 Overview of goals, course development and research at Stanford

John C. Mitchell (Stanford University, US)

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Over the last two years, over 100 faculty have developed close to 200 online course activities on campus and for public release. Our support team combines instructional designers, video producers, and software platform developers. We also are developing an iterative cycle combining course development with research. As research examples, the talk will summarize current research on attrition, interventions to increase success, and demographics of public course participation.

3.18 Designing Massive Scale Social Learning

Mike Sharples (The Open University – Milton Keynes, GB)

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A central challenge for developers of MOOC platforms and courses is to understand which pedagogies can be effective at massive scale, and how. One underpinning theory is Metcalfe's Law which states that the value of a networked product or service increases with the number of people using it. Thus, the effectiveness of networked or connectivist learning ought to increase with scale. But as Stephen Downes has indicated, people are not just nodes in a data network, they engage in meaningful communication, so we need to understand meaning making at massive scale – in particular how that can be orchestrated for productive learning. Other pedagogies may be impervious to scale – e.g. delivery or broadcasting of learning materials – but we should understand the distinctive changes in these pedagogies from face-to-face teaching, through small-scale online learning, to massive-scale access. Other pedagogies may degrade with scale, such as embodied learning (it is not as easy to teach a dance or surgery class at massive scale). What are the opportunities and problems of scale for pedagogies that are not currently supported by most MOOCs, including inquiry-based, reflective, collaborative, problem-based, game-based, and case-based learning?

3.19 Towards sMOOCs

Marcus Specht (Open University – Heerlen, NL)

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Legacy, experiences, and development around open online education at the OU and Welten Institute (former CELSTEC).

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3.20 E-Learning and MOOCs at LMU

Martin Wirsing (LMU München, DE)

Since more than ten years. LMU München is engaged in supporting learning and teaching by digital media. This includes research and teaching audio and video recordings with iTunesU, e-learning courses with the Virtual University of Bavaria (vhb), digital recording of large lectures, and e-learning research. LMU was also the first German university offering MOOCs on the Coursera platform. This talk gives a short overview of the e-learning and MOOC activities of LMU.

3.21 MOOC and Further Education – How universities with MOOC may impact the further education market

Volker Zimmermann (IMC AG – Saarbrücken, DE)

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Most MOOC initiatives today focus on the higher education segment. Universities produce MOOCs primarily for the target group of students. However the further education and professional training market is maybe the bigger market. Employees in companies can benefit very much from high-quality online education delivered by academic institutions, as otherwise there are not many alternatives when being full time at work. Going back to university in a face to face course is very difficult, but getting courses from the own university by using them online to get latest insight information and knowledge with link to research results if of great value for many academic employees in business. Volker Zimmermann presented the business experiences of conceptualization and realization of MOOCs for the professional training market. IMC AG explores how university MOOC strategies might look like when aiming to deliver education to companies. The design and implementation of MOOC might be different to the delivery to students. Development Methodologies and instructional designs should focus on the needs of this target group more. In addition, learning platforms will need different functionality to support the corporate specific use cases. Based on IMC Learning Suite and within the Corporate MOOC platform "OpenCourseWorld.com", IMC has proved that there is interest and potential to serve the market of professional trainings for corporate employees.

4 Working Groups

4.1 Report of the Workshop on Multidisciplinary Research for Online Education

Douglas Fisher and Armando Fox

In February 2013 the Computing Community Consortium (CCC) sponsored the Workshop on Multidisciplinary Research for Online Education (MROE) (http://www.cra.org/ccc/ visioning/visioning-activities/online-education). This visioning activity explored the research opportunities at the intersection of the learning sciences, and the many areas of computing, to include human-computer interactions, social computing, artificial intelligence, machine learning, and modeling and simulation.

The workshop was motivated and informed by high profile activities in massive, open, online education (MOOE). Point values of "massive" and "open" are extreme values that make explicit, in ways not fully appreciated previously, variability along multiple dimensions of scale and openness. The report for MROE has been recently completed and is online (http://www.cra.org/ccc/files/docs/CCC-MROE-Report.pdf). It summarizes the workshop activities and format, and synthesizes across these activities, elaborating on 4 recurring themes:

- 1. Next Generation MOOCs and Beyond MOOCs;
- 2. Evolving Roles and Support for Instructors;
- 3. Characteristics of Online and Physical Modalities;
- 4. Physical and Virtual Community.

5 Research questions

The development of MOOCs creates new research problems and new methods to address some of them.

The new research problems come from the will to make MOOC platforms and MOOCs more diverse, ethical, enjoyable, adaptive, evaluable, accessible, usable by underserved learners, aware of cultural diversity, etc.

- **Diverse:** not all courses are organized around the talk of a professor. More research is needed to understand how to make MOOCs more diverse, by integrating multi-modal user interfaces, remote labs, etc. in order to implement active pedagogy in MOOCs.
- **Ethical:** more research on ethic is needed to understand which kind of information should be accessible to whom, focusing on the privacy issues related to the data produced by the students. Besides defining goals, research is also needed to understand their implementation in MOOC platforms, requiring, for instance, to develop privacy models and methods to develop MOOC platforms in such a way privacy is enforced by design.
- **Enjoyable:** children lean a lot by playing games. Leaning is also often enjoyable. These two remarks led to the idea to investigate how courses could be gamified, that is transformed into educational games.

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- **Adaptive:** in a classroom pedagogy, there is little room for offering each learner a particular path through knowledge : a particular sequence of exercises adapt to the level and the difficulties of each student. With MOOCs, such an adaptation to the learner becomes possible, but a lot of research is needed to understand which algorithm permit this adaptation.
- **Adaptable:** more research is needed to give the learners more feedback, by correcting exercices automatically or by the peers, and also to evaluate their success and deliver diplomas.
- **Evaluable:** more research is needed to evaluate the quality of a MOOC, besides the number of learners, the drop rate, and the reputation of the course.
- **Accessible:** current MOOC platforms are difficult to use by deaf, blind, etc. learners. More research is needed to understand how to make them accessible.
- **Usable by to underserved learners:** MOOCs are sometimes thought as a way to drive illiterate adults and droppers back to school. But specific strategies, interfaces, etc. are needed for these specific learners.
- Aware of cultural diversity: offering courses in different languages is essential for offering education to everyone. Besides the diversity of languages, more research is needed to present the courses and the exercises in a way that is compatible with the different (academic) cultures.

On the other hand, MOOCs platforms can serve as a measuring instrument in pedagogy. The history of each science can be divided into two eras : the first when the scientists do not use any measuring instrument and the second where they do. For instance, astronomy was first naked eye astronomy and then has been instrumented since Galileo's telescope, Biology has been instrumented since van Leeuwenhoek's microscope, but mathematics have been instrumented only since the middle of seventies (of the 20th century) and the use of a computer to prove the four color theorem. If the computer is the mathematician's telescope, the network may be the social scientist's telescope, as it permit to observe on a large scale social interactions. This is particularly the case with pedagogy: MOOCs permit to observe on a large scale how people teach, how people learn, etc.

Developping this instrumented pedagogy requires to develop the analysis of learner traces

Finally more research is needed to understand how MOOCs can integrate in current frameworks : how is it possible to transform on-line communities into geographical ones, what are the different business models to develop MOOCs and MOOC platforms, how to balance the efforts of private industry and public services, etc.



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Report from Dagstuhl Seminar 14121

Computational Complexity of Discrete Problems

Edited by

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- Abstract -

This report documents the program and the outcomes of Dagstuhl Seminar 14121 "Computational Complexity of Discrete Problems". The first section gives an overview of the topics covered and the organization of the meeting. Section 2 lists the talks given in chronological order. The last section contains the abstracts of the talks.

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1 **Executive Summary**

Anna Gal Michal Koucký Oded Regev Rüdiger Reischuk

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Introduction and goals

Computational complexity aims to answer what is efficiently solvable and what is not on various computational models. This means providing upper and lower bounds on the necessary resources such as time, space or communication, and establishing connections among the different models.

There are intricate connections between complexity measures in different computational models. For instance, circuit size is closely related to computation time, whereas circuit depth and branching program size are closely related to computation space. Breaking the current barriers of our understanding in any of these models would have major consequences in several of the other models as well.

Investigating the connections between the various computational models and subareas of computational complexity has already led to many exciting results. In recent years several novel techniques have been introduced in computational complexity, resulting in a number



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of breakthroughs, some of which are still actively investigated. In particular, informationtheoretic techniques have led to tremendous progress in our understanding of communication complexity, such as new methods to compress interactive communication, very efficient ways to immunize protocols against corruption of the communication by an adversary, and a better understanding of so-called direct product questions. This progress in turn led to progress in our understanding of the streaming model, in which one needs to process massive amounts of received data without being able to store it. Semi-definite programming, a technique originally used in optimization and in the design of approximation algorithms, has led to a tight and very elegant characterization of quantum query complexity. In the area of hardness of approximation, new approaches to prove the Unique Game Conjecture (which is one of the most central open questions in the area) have been suggested. Finally, a recent breakthrough separation of the class NEXP (nondeterministic exponential time) from the class ACC^{0} (bounded depth circuits with counting) rests on a new technique that derives a lower bound for a non-uniform model from an upper bound on satisfiability in the uniform setting; this technique opens up a new range of possible connections between uniform and non-uniform models.

The seminar "Computational Complexity of Discrete Problems" has evolved out of the series of seminars entitled "Complexity of Boolean Functions," a topic that has been covered at Dagstuhl on a regular basis since the foundation of this research center. A salient feature of the current research in computational complexity is the integration of ideas from different subareas of computational complexity and from other fields in computer science and mathematics. By organizing a generic seminar on computational complexity we have aimed to attract researchers from those various subareas and foster further fruitful interactions.

Organization of the meeting

43 researches from around the world participated in the seminar including a substantial number of young researchers. Each day, Monday to Thursday, we started by a longer talk surveying recent results in specific areas that were chosen beforehand. We had the following survey talks:

- Shubhangi Saraf: Recent developments in arithmetic circuits
- Subhash Khot: On the unique games conjecture and the approximation resistance of predicates.
- Mark Braverman: Recent progress on interactive error correction: an overview.
- Ankur Moitra: Extended formulations and information complexity.

Additionally, on Friday we started with a survey on recent progress in algorithms for matrix multiplication presented by Chris Umans. The tutorials were followed by shorter talks by other participants. Afternoons were reserved for discussions in impromptu groups. In late afternoon on Monday, Tuesday and Thursday we had several additional short talks. On Wednesday evening we organized a rump session where everyone could present an open problem or announce a new result. One of the open problems from this session on the relationship between information cost and communication complexity presented by Omri Weinstein was very recently resolved.

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Topics covered by the seminar

The talks of the workshop fit into several subareas of computational complexity. We summarize the talks next. Detailed abstracts of the talks can be found at the end of this report.

Circuit complexity

One of the goals in circuit complexity is to prove strong lower bounds on the size of circuits computing explicit functions. Even in the case of bounded depth circuits the known lower bounds deteriorate quickly with depth. Oded Goldreich discussed approaches to prove strong lower bounds of almost the type $2^{\Omega(n)}$ in such a setting by focusing on certain kinds of multilinear functions.

Another approach to proving lower bounds was presented by Anup Rao, who showed new lower bounds for bounded-depth circuits with arbitrary gates when the fan-in of gates is strictly smaller than n.

Valentine Kabanets considered the interplay between Boolean formulas and harmonic analysis of functions computed by Boolean formulas. He showed that functions represented by sub-quadratic formulas over the basis AND, OR and NOT have constrained Fourier coefficients. Among other things, this fact leads to new learning algorithms for such functions.

Shubhangi Saraf reviewed recent progress towards separating Valiant's classes VP and VNP, the arithmetic analogues of P and NP.

Eric Allender in his talk focused on another aspect of circuit complexity by providing improved upper bounds on the level of counting hierarchy in which certain problems involving arithmetic circuits lie.

Beside proving lower bounds several talks also focused on algorithmic aspects of circuits. Kristoffer Arnsfelt Hansen discussed the circuit complexity of several graph problems when the graphs have bounded cut-width, and Swastik Kopparty showed in his talk an efficient way of indexing irreducible polynomials over finite fields which may serve as a useful tool in designing efficient arithmetic circuits.

Amir Yehudayoff studied the growth rate of symmetric polynomials with possible applications in pseudorandomness.

Communication complexity and its applications

The classical theory of error correcting codes addresses mainly the question of one-way communication over unreliable channel. In communication complexity the main issue is to minimize the amount of communication between two interacting parties whose goal is to evaluate some joint function of their respective inputs. In this scenario the communication goes both ways. Mark Braverman gave a summary of results on error correcting techniques when the two parties communicate over unreliable channel.

Pavel Pudlák presented approaches to constructing good error correcting codes for interactive communication (so-called tree codes) based on properties of certain matrices.

Another popular research topic in communication complexity is information complexity. This topic was discussed by Omri Weinstein. He showed a new technique to estimate interactively the amount of information leaked by the two players about their inputs during a two party communication. This might have applications for secure communication.

Hartmut Klauck presented an interplay between quantum and classical communication, and established that in certain setting quantum communication can be replaced by classical messages.

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Mike Saks provided a surprisingly simple protocol for certain class of functions in the number-on-the-forehead multi-party model.

Ankur Moitra presented a survey on recent results regarding extended formulation approach to solving hard combinatorial problems. In this context he also successfully applied techniques from communication complexity.

Communication complexity is a major tool in the analysis of data stream algorithms, algorithms that can process huge data sets while utilizing only little memory. David Woodruff presented a surprising fundamental result showing that a large class of streaming algorithms can be simulated using only linear sketches of the data stream. This could simplify design of data stream algorithms.

Amit Chakrabarti considered a model for processing large data streams with the help of an untrusted but powerful helper (e.g. cloud service). He discussed a relationship between this model and Arthur Merlin communication protocols.

Inapproximability

When we lack efficient algorithms for various problems that are NP-complete we may try to solve them approximately. In some cases, even that is hard as demonstrated by Prahladh Harsha in his talk on inapproximability of coloring of hypergraphs.

On the other hand, Johan Håstad presented a new algorithm for finding a satisfying solution to a CNF formula when all clauses in the formula can simultaneously be satisfied by majority of their literals. When the formula does not have such a property the problem becomes NP-complete.

Irit Dinur discussed her results on testing whether a given function is a direct product of some function with application to parallel repetition, and Eli Ben-Sasson explained his result on constructing linear-size probabilistically checkable proofs (PCP) that can be checked using n^{ϵ} queries.

Pseudorandomness

Construction of pseudorandom generators for Boolean circuits is currently reasonably well understood. However, in non-Boolean setting such as in the case of multi-output functions or arithmetic circuits we still lack good understanding of the problem. Ronen Shaltiel presented pseudorandom generators with optimal seed length for multi-output functions computed by polynomial size circuits, and Amnon Ta-Shma presented a new construction of hitting set generators for low-degree polynomials.

A central problem for which we know a very efficient randomized algorithm but no deterministic one is the problem of testing whether a polynomial is identically zero. Meena Mahajan considered the problem of testing whether a polynomial represented by an arithmetic formula that reads each variable at most three times is zero or not. She provided a deterministic algorithm for this problem.

Amir Shpilka presented a new algorithm for the closely related problem of testing whether two polynomials are the same up to a linear transformation of variables.

Other models

Harry Buhrman presented a new model of computation, catalytic space, in which in addition to the usual limited work space we have essentially unlimited amount of extra space which is however full of data that have to be preserved. He exhibited the surprising power of this

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extra space that allows one to compute functions that we do not know how to compute using only the limited work space.

Matchias Krause discussed the issue of cryptographic authentication by devices with limited resources which are not able to evaluate the standard cryptographic primitives like RSA and AES. He proposed solutions for those situations and reported on an actual implementation.

Jaikumar Radhakrishnan considered the bit-probe complexity of a data structure for storing sets (set-membership problem). He presented a very elegant and more efficient solution for this problem.

Thomas Thierauf presented an algorithm to compute the number of perfect matchings in K_5 -free graphs. In general graphs this problem is considered to be hard.

Till Tantau talked about parallel algorithms in the context of fixed parameter tractability. He defined the notion and presented parallel algorithms in that context.

Chris Umans presented an overview of recent progress on matrix multiplication.

Conclusion

Understanding the computational complexity of various problems is the primary goal of theory of computing. In the past several years there has be tremendous progress in various areas of complexity for example, in communication complexity, arithmetic circuit complexity and derandomization. This progress brings us closer to the goal of understanding computation. Yet, as we have seen new relevant concepts and models emerge, e.g., information cost and catalytic computation. Despite all the progress that have been achieved since our previous meeting three years ago, and in the light of the new developments, there is a general consensus among the participants of the seminar that there is still long way ahead of us before we gain a good understanding of limits of efficient computation and resolve many of the central problems in computational complexity.

We like to thank the staff at Dagstuhl who – as usual – provided a marvelous surrounding to make this a successful meeting with ample space for undisturbed interactions between the participants.

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3 Overview of Talks

3.1 Small circuits and big numbers; Better bounds on computing the bits of arithmetic circuits

Eric Allender (Rutgers University – Piscataway, US)

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 Joint work of Allender, Eric; Balaji, Nikhil; Datta, Samir
 Main reference E. Allender, N. Balaji, S. Datta, "Low-depth Uniform Threshold Circuits and the Bit-Complexity of Straight Line Programs," ECCC TR13-177, 2013.
 URL http://eccc.hpi-web.de/report/2013/177/

Earlier work had shown that, given an arithmetic circuit C and a number i, the problem of computing the *i*-th bit of the number represented by C lies in the counting hierarchy – way up in the counting hierarchy. We knock one level off of that bound, and show that several other problems lie in the same level. The talk won't focus on the details, which can be found in [ECCC TR13-177]. Instead, the talk will present lots of intriguing open questions, and will also attempt to explain why it is interesting to consider the complexity of problems that deal with computing the bits of very big numbers.

3.2 Constant rate PCPs for circuit-SAT with sublinear query complexity

Eli Ben-Sasson (Technion – Haifa, IL)

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 Joint work of Ben-Sasson, Eli; Kaplan, Yohay; Kopparty, Swastik; Meir, Or; Stichtenoth, Henning

 Main reference E. Ben-Sasson, Y. Kaplan, S. Kopparty, O. Meir, H. Stichtenoth, "Constant Rate PCPs for Circuit-SAT with Sublinear Query Complexity," in Proc. of the 54th Annual IEEE Symp. on Foundations of Computer Science (FOCS'13), pp. 320–329, IEEE CS, 2013.

URL http://dx.doi.org/10.1109/FOCS.2013.42

The PCP theorem (Arora et. al., J. ACM 45(1,3)) says that every NP-proof can be encoded to another proof, namely, a probabilistically checkable proof (PCP), which can be tested by a verifier that queries only a small part of the PCP. A natural question is how large is the blow-up incurred by this encoding, i.e., how long is the PCP compared to the original NP-proof. The state-of-the-art work of Ben-Sasson and Sudan (SICOMP 38(2)) and Dinur (J. ACM 54(3)) shows that one can encode proofs of length n by PCPs of length $n \log^{O(1)} n$ that can be verified using a constant number of queries. In this work, we show that if the query complexity is relaxed to n, then one can construct PCPs of length O(n) for circuit-SAT, and PCPs of length $O(t \log t)$ for any language in NTIME(t).

More specifically, for any $\epsilon > 0$ we present (non-uniform) probabilistically checkable proofs (PCPs) of length $2^{O(1/\epsilon)}n$ that can be checked using n^{ϵ} queries for circuit-SAT instances of size n. Our PCPs have perfect completeness and constant soundness. This is the first constant-rate PCP construction that achieves constant soundness with nontrivial query complexity (o(n)).

Our proof replaces the low-degree polynomials in algebraic PCP constructions with tensors of transitive algebraic geometry (AG) codes. We show that the automorphisms of an AG code can be used to simulate the role of affine transformations which are crucial in earlier high-rate algebraic PCP constructions. Using this observation we conclude that

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any asymptotically good family of transitive AG codes over a constant-sized alphabet leads to a family of constant-rate PCPs with polynomially small query complexity. Such codes are constructed in the appendix to this paper for the first time for every message length, after they have been constructed for infinitely many message lengths by Stichtenoth [Trans. Information Theory 2006].

3.3 Recent progress on interactive error correction: an overview

Mark Braverman (Princeton University, US)

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Classical error-correcting codes deal with the problem of data transmission over a noisy channel. There are efficient error-correcting codes that work even when the noise is adversarial. In the interactive setting, the goal is to protect an entire conversation between two (or more) parties from adversarial errors. The area of interactive error correcting codes has experienced a substantial amount of activity in the last few years. In this talk we will introduce the problem of interactive error-correction and discuss some of the recent exciting progress towards its resolution.

3.4 Catalytic space

Harry Buhrman (CWI – Amsterdam, NL)

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 Joint work of Buhrman, Harry; Cleve, Richard; Koucký, Michal; Loff, Bruno; Speelman, Florian

We define the notion of a *catalytic-space* computation. This is a computation that has a small amount of clean space available and is equipped with additional auxiliary space, with the caveat that the additional space is initially in an arbitrary, possibly incompressible, state and must be returned to this state when the computation is finished. We show that the extra space can be used in a nontrivial way, to compute uniform TC1-circuits with just a logarithmic amount of clean space. The extra space thus works analogously to a catalyst in a chemical reaction. TC1- circuits can compute for example the determinant of a matrix, which is not known to be computable in logspace.

In order to obtain our results we study an algebraic model of computation, a variant of straight-line programs. We employ register machines with input registers x_1, \ldots, x_n and work registers r_1, \ldots, r_m . The instructions available are of the form $r_i := r_i \pm u \cdot v$, with u, v registers (distinct from r_i) or constants. We wish to compute a function $f(x_1, \ldots, x_n)$ through a sequence of such instructions. The working registers have some arbitrary initial value $r_i = t_i$, and they may be altered throughout the computation, but by the end all registers must be returned to their initial value t_i , except for, say, r_1 which must hold $t_1 + f(x_1, \ldots, x_n)$. We show that all of Valiant's class VP, and more, can be computed in this model. This significantly extends the framework and techniques of Ben-Or and Cleve.

Upper bounding the power of catalytic computation we show that catalytic logspace is contained in ZPP. We further construct an oracle world where catalytic logpace is equal to PSPACE, and show that under the exponential time hypothesis (ETH), SAT can not be computed in catalytic sub-linear space.
3.5 Arthur, Merlin, and data stream computation

Amit Chakrabarti (Dartmouth College – Hanover, US)

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Amit Chakrabarti

Joint work of Chakrabarti, Amit; Cormode, Graham; McGregor, Andrew; Thaler, Justin; Venkatasubramanian, Suresh

Main reference A. Chakrabarti, G. Cormode, A. McGregor, J. Thaler, "Annotations in Data Streams," ECCC TR12-022, 2012. URL http://eccc.hpi-web.de/report/2012/022/

A series of recent works have developed a theory of computation wherein a space-limited algorithm tasked with answering questions about a massive data stream gets to interact with a powerful space-unbounded helper, thereby expanding its computational power. The streaming verifier is unwilling to blindly trust answers returned by the helper. How can we design a suitable protocol that allows the helper to not just supply an answer to the verifier but convince her that the answer is correct?

We shall describe a few of the most important algorithms in this model developed to date. We shall see that for several well-studied data stream problems, access to the helper results in significant space savings for the verifier: sometimes quadratic, sometimes even exponential.

We shall then turn to lower bounds in this model, which will naturally lead us to Arthur-Merlin communication complexity. Our work gives a number of new results about this kind of communication. In particular, we bring out the importance of the amount of interactivity between Arthur and Merlin.

3.6 Direct product testing

Irit Dinur (Weizmann Institute, IL)

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© Irit Dinur Joint work of Dinur, Irit; Steurer, David

Main reference I. Dinur, D. Steurer, "Direct Product Testing," in Proc. of the 2014 IEEE Conf. on Computational Complexity (CCC'14), to appear; pre-print available as ECCC TR13-179 (2013). URL http://eccc.hpi-web.de/report/2013/179/

The k-fold direct product of a function $f: [n] \to \{0,1\}$ is a new function that gives the local evaluation of the original function on all k-windows; $F: [n]^k \to \{0,1\}^k$ defined by $F(x_1,...,x_k) = (f(x_1),...,f(x_k))$. The direct product testing question is to test whether a given function F is (close to) an honest direct product. The test is simple: choose two local windows that intersect, and check consistency on the intersection. Surprisingly, the analysis is very tricky.

Proving that this test works entails lifting locally-consistent substrings to a globally consistent one. We prove that such lifting works in a comprehensive parameter setting, allowing non-trivial lifting already when the local consistency is above the minimum threshold of exp(-k).

We also discuss connections of this question to parallel repetition through the "confuse and compare" game.

3.7 Boolean circuits of depth three and arithmetic circuits with arbitrary gates

Oded Goldreich (Weizmann Institute, IL)

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 Joint work of Goldreich, Oded; Wigderson, Avi
 Main reference O. Goldreich, A. Wigderson, "On the Size of Depth-Three Boolean Circuits for Computing Multilinear Functions," ECCC TR13-043, 2013.
 URL http://eccc-preview.hpi-web.de/report/2013/043/

This paper introduces and initiates a study of a new model of arithmetic circuits coupled with new complexity measures. The new model consists of multilinear circuits with arbitrary multilinear gates, rather than the standard multilinear circuits that use only addition and multiplication gates. In light of this generalization, the arity of gates becomes of crucial importance and is indeed one of our complexity measures. Our second complexity measure is the number of gates in the circuit, which (in our context) is significantly different from the number of wires in the circuit (which is typically used as a measure of size). Our main complexity measure, denoted C, is the maximum of these two measures (i.e., the maximum between the arity of the gates and the number of gates in the circuit). We also consider the depth of such circuits, focusing on depth-two and unbounded depth.

Our initial motivation for the study of this arithmetic model is the fact that the two main variants (i.e., depth-two and unbounded depth) yield natural classes of depth-three Boolean circuits for computing multi-linear functions. The resulting circuits have size that is exponential in the new complexity measure. Hence, lower bounds on the new complexity measure yield lower bounds on a restricted class of depth-three Boolean circuits (for computing multi-linear functions). Such lower bounds are a sanity check for our conjecture that multilinear functions of relatively low degree over GF(2) are good candidates for obtaining exponential lower bounds on the size of constant-depth Boolean circuits (computing explicit functions). Specifically, we propose to move gradually from linear functions to multilinear ones, and conjecture that, for any $t \geq 2$, some explicit t-linear functions $F : (\{0,1\}^n)^t \to \{0,1\}$ require depth-three circuits of size $\exp(\Omega(tn^{t/(t+1)}))$.

Letting C_2 denote the complexity measure C, when minimized over all depth-two circuits of the above type, our main results are as follows.

- 1. For every t-linear function F, it holds that $C(F) \leq C_2(F) = O((tn)^{t/(t+1)})$.
- 2. For almost all t-linear function F, it holds that $C_2(F) \ge C(F) = \Omega((tn)^{t/(t+1)})$.
- 3. There exists a bilinear function F such that $C(F) = O(\sqrt{n})$ but $C_2(F) = \Omega(n^{2/3})$.

The main open problem posed in this paper is proving a result analogous to (2) for an explicit function F. For starters, we seek lower bound of $\Omega((tn)^{0.51})$ for an explicit t-linear function F, preferably for constant t. We outline an approach that reduces this challenge (for t = 3) to a question regarding matrix rigidity.

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3.8 Circuit complexity of properties of graphs with constant planar cutwidth

Kristoffer Arnsfelt Hansen (Aarhus University, DK)

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 Joint work of Hansen, Kristoffer Arnsfelt; Komarath, Balagopal; Sarma M. N., Jayalal; Skyum, Sven;
 Talebanfard, Navid

We study the complexity of several of the classical graph decision problems in the setting of bounded cutwidth and how imposing planarity affects the complexity. We show that for 2-coloring, for bipartite perfect matching, and for several variants of disjoint paths the straightforward NC^1 upper bound may be improved to $AC^0[2]$, ACC^0 , and AC^0 respectively for bounded planar cutwidth graphs. On the other hand we show that 3-coloring and Hamilton cycle remain hard for NC^1 , analogous to the NP-completeness for general planar graphs. We also show that 2-coloring and (non-bipartite) perfect matching are hard for certain subclasses of $AC^0[2]$. In particular this shows that our bounds for 2-coloring are quite close.

3.9 Improved inapproximability results for hypergraph coloring

Prahladh Harsha (TIFR Mumbai, IN)

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Joint work of Guruswami, Venkat; Harsha, Prahladh; Håstad, Johan; Srinivasan, Srikanth; Varma, Girish

Main reference V. Guruswami, J. Håstad, P. Harsha, S. Srinivasan, G. Varma, "Super-polylogarithmic hypergraph coloring hardness via low-degree long codes," arXiv:1311.7407v1 [cs.CC], 2013. URL http://arxiv.org/abs/1311.7407v1

Despite the tremendous progress in understanding the approximability of several problems, the status of approximate coloring of constant colorable (hyper)graphs is not resolved and in fact, there is an exponential (if not doubly exponential) gap between the best known approximation algorithms and inapproximability results. The best known approximation algorithms which are a combination of combinatorial and semi-definite programming methods, require at least n^{δ} colors to color a 2 colorable 4-uniform hypergraph for some constant delta in (0,1). On the contrary, till recently, the best known hardness results could rule out at best coloring a 2-colorable hypergraph with polylog n colors (if not polyloglog n colors in some cases).

Recently, with the discovery of the low-degree polynomial long code (aka short code of Barak et al [FOCS 2012]), there has been a super-polynomial (and in some cases, exponential) improvement in the inapproximability results. In particular, we prove quasi-NP-hardness of the following problems on n-vertex hypergraphs:

Coloring a 2-colorable 8-uniform hypergraph with $2^{2^{\sqrt{\log \log n}}}$ colors.

Coloring a 4-colorable 4-uniform hypergraph with $2^{2^{\sqrt{\log \log n}}}$ colors

Coloring a 3-colorable 3-uniform hypergraph with $(\log n)^{1/\log \log \log n}$ colors.

These results are obtained using the low-degree polynomial code and the techniques proposed by Dinur and Guruswami [FOCS 2013] to incorporate this code for inapproximability results.

In this talk, I'll explain the bottleneck in obtaining improved coloring inapproximability results using the long code and how derandomizations of the long code (the short code in our setting) can be used to improve the inapproximability factors.

3.10 $(2 + \epsilon)$ -SAT is NP-hard

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Main reference P. Austrin, V. Guruswami, J. Håstad, "(2 + ϵ)-SAT is NP-hard, ECCC TR13-159, 2013. URL http://eccc.hpi-web.de/report/2013/159/

We prove the following hardness result for a natural promise variant of the classical CNFsatisfiability problem: Given a CNF-formula where each clause has width w and the guarantee that there exists an assignment satisfying at least g < w/2 literals in each clause, it is NP-hard to find a satisfying assignment to the formula (that sets at least one literal to true in each clause). On the other hand, when g is at least w/2, it is easy to find a satisfying assignment via simple generalizations of the algorithms for 2-Sat.

3.11 Small de Morgan formulas make low-frequency sound: Fourier concentration from shrinkage

Valentine Kabanets (Simon Fraser University – Burnaby, CA)

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 Joint work of Impagliazzo, Russell; Kabanets, Valentine
 Main reference R. Impagliazzo, V. Kabanets, "Fourier concentration from shrinkage," in Proc. of the 2014 IEEE Conf. on Computational Complexity (CCC'14), to appear.

A standard complexity-theoretic way to measure the complexity of a Boolean function is via the size of a smallest algorithm (circuit or formula) computing (or approximating) the function. Another way to measure the complexity of a function is via the sparsity of its Fourier decomposition, e.g., the concentration of its Fourier mass on some subset of frequencies. The celebrated result of Linial, Mansour, and Nisan (1993) was the first to establish a connection between circuit complexity and Fourier complexity: they showed that the class of Boolean functions computable by polysize AC0 circuits (generalization of CNF/DNFs to arbitrary constant depth) exhibit sharp concentration of the Fourier spectrum over the set of low frequencies (of polylogarithmic weight).

In this talk, I will present analogous results for the class of Boolean functions computable by de Morgan formulas (using AND, OR, and NOT gates) of sub-quadratic size. The Fourier concentration for such functions is over the frequencies related to the *shrinkage exponent*: the quantity measuring how much the formulas reduce in size when hit with random restrictions of the variables. Namely, we show for an *n*-variate Boolean function *f* computable by a formula of size *s*, that the Fourier mass of *f* over the frequencies higher than $s^{1/\Gamma+\epsilon}$ is at most $exp(-n^{\epsilon/3})$, where Γ is the shrinkage exponent for the corresponding class of formulas: $\Gamma = 2$ for general formulas, and $\Gamma = \approx 3.27$ for read-once formulas. We prove that this Fourier concentration is essentially optimal.

As an application, we get that subquadratic-size formulas have negligible correlation with parity, and are learnable under the uniform distribution, and also lossily compressible, in subexponential time. We also prove tight bounds on the average sensitivity of read-once formulas.

3.12 Two results about quantum messages

Hartmut Klauck (Nanyang TU - Singapore, SG)

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 Joint work of Klauck, Hartmut; Podder, Supartha
 Main reference H. Klauck, S. Podder, "Two Results about Quantum Messages," arXiv:1402.4312v2 [quant-ph], 2014.
 URL http://arxiv.org/abs/1402.4312v2

We show two results about the relationship between quantum and classical messages. Our first contribution is to show how to replace a quantum message in a one-way communication protocol by a deterministic message, establishing that for all partial Boolean functions $f : \{0,1\}^n \times \{0,1\}^m \to \{0,1\}$ we have $D^{A\to B}(f) \leq O(Q^{A\to B,*}(f) \cdot m)$. This bound was previously known for total functions, while for partial functions this improves on results by Aaronson, in which either a log-factor on the right hand is present, or the left hand side is $R^{A\to B}(f)$, and in which also no entanglement is allowed.

In our second contribution we investigate the power of quantum proofs over classical proofs. We give the first example of a scenario, where quantum proofs lead to exponential savings in computing a Boolean function. The previously only known separation between the power of quantum and classical proofs is in a setting where the input is also quantum.

We exhibit a partial Boolean function f, such that there is a one-way quantum communication protocol receiving a quantum proof (i.e., a protocol of type QMA) that has cost $O(\log n)$ for f, whereas every one-way quantum protocol for f receiving a classical proof (protocol of type QCMA) requires communication $\Omega(\sqrt{n}/\log n)$.

3.13 Indexing irreducible polynomials over finite fields

Swastik Kopparty (Rutgers University – Piscataway, US)

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Swastik Kopparty
Joint work of Kopparty, Swastik; Kumar, Mrinal; Saks, Michael

Let S be the set of degree n irreducible polynomials over the finite field F_q . We show that there exists circuits of size $poly(n, \log q)$ which compute a bijection from $\{1, 2, ..., |S|\}$ to S.

3.14 On ultralightweight authentication

Matthias Krause (Universität Mannheim, DE)

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In many application areas for ultra-lightweight devices, like passively powered RFIDs, there is a need of authenticity. However, most standard cryptographic algorithms like AES and RSA are not suited for implementation on such devices. This motivated an intense search for new approaches to ultra-lightweight authentication in the last years. It is known that Challenge-Response Protocols based on ultra-lightweight blockciphers like PRESENT solve this task sufficiently good w.r.t. to area, communication complexity and energy consumption. We study the question whether other approaches like HB-protocols or linear protocols can

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be used to obtain better solutions and get partially a positive answer. Moreover, we present a stream cipher based approach to ultralightweight authentication called Double Streaming, which is provable secure in a generic scenario, and which has the potential to beat existing solutions.

3.15 Testing read-restricted formulas.

Meena Mahajan (The Institute of Mathematical Sciences, IN)

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Joint work of Mahajan, Meena; Rao, B. V. Raghavendra; Sreenivasaiah, Karteek

Main reference M. Mahajan, B. V. R. Rao, K. Sreenivasaiah, "Monomials, Multilinearity and Identity Testing in Simple Read-Restricted Circuits," Theoretical Computer Science, Vol. 524, pp. 90–102, 2014. URL http://dx.doi.org/10.1016/j.tcs.2014.01.005

How do we test whether a given arithmetic circuit computes the identically zero polynomial? Efficient algorithms are known for special types of bounded-depth formulas, and special types of read-restricted multilinear formulas. We describe how to test read-twice or read-thrice formulas without any depth or multilinearity restrictions. We also describe an approach for testing the sum of two unbounded products of read-once formulas; this approach works over the integers but can hopefully be extended to other rings.

This is joint work with B V Raghavendra Rao and Karteek Sreenivasaiah, and is reported in papers in Theoretical Computer Science 524:90–102, 2014 (preliminary version in MFCS 2012) and in COCOON 2014.

Funded by an IMPECS project.

3.16 Extended formulations and information complexity

Ankur Moitra (MIT – Cambridge, US)

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 Joint work of Braverman, Mark; Moitra, Ankur
 Main reference M. Braverman, A. Moitra, "An Information Complexity Approach to Extended Formulations," in Proc. of the 45th Annual ACM Symp. on Theory of Computing (STOC'13), pp. 161-170, ACM, 2013; pre-print available as ECCC TR12-131 (2012).
 URL http://dx.doi.org/10.1145/2488608.2488629
 URL http://ecc.hpi-web.de/report/2012/131/

We survey some of the recent lower bounds for extended formulations. Our emphasis is on the underlying techniques, and parallels to the techniques used in lower bounds for communication complexity.

3.17 Tree codes and triangular totally nonsingular matrices

Pavel Pudlák (Academy of Sciences – Prague, CZ)

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Main reference P. Pudlák, "Linear tree codes and the problem of explicit constructions," arXiv:1310.5684v3 [cs.IT], 2014.

URL http://arxiv.org/abs/1310.5684v3

We reduce the problem of constructing asymptotically good tree codes to the construction of triangular totally positive matrices over fields with polynomially many elements.

3.18 Set membership with two bit probes

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 Joint work of Garg, Mohit; Radhakrishnan, Jaikumar
 Main reference N. Alon, U. Feige, "On the power of two, three and four probes," in Proc. of the 20th Annual ACM-SIAM Symp. on Discrete Algorithms (SODA'09), pp. 346–354, SIAM, 2009.
 URL http://dx.doi.org/10.1137/1.9781611973068.39

We will consider the bit-probe complexity of the set membership problem, where a set S of size at most n from a universe of size m is to be represented as a short bit vector in order to answer membership queries of the form "Is x in S?" by adaptively probing the bit vector at t places. Let s(m, n, t) be the minimum number of bits of storage needed for such a scheme. Alon and Feige showed that for t = 2 (two bit probes), such schemes can be obtained from dense graphs with large girth. In particular, they showed that for $n < \log m$,

 $s(m, n, 2) = O(mn \log((\log m)/n) / \log m).$

We improve their analysis and obtain a better upper bound; by modelling two-probe schemes as graphs and considering their girth, we obtain a corresponding lower bound.

(a) There is a constant C > 0, such that for all large m,

 $s(m, n, 2) \le C \cdot m^{1 - \frac{1}{4n+1}}.$

(b) There is a constant D > 0, such that for $n \ge 4$ and all large m, we have

$$s(m, n, 2) \ge D \cdot m^{1 - \frac{1}{\lfloor n/4 \rfloor}}.$$

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3.19 Circuits with medium fan-in

Anup Rao (University of Washington – Seattle, US)

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 Main reference P. Hrubes, A. Rao, "Circuits with Medium Fan-In," ECCC TR14-020, 2014. URL http://eccc.hpi-web.de/report/2014/020/

We consider boolean circuits in which every gate may compute an arbitrary boolean function of k other gates, for a parameter k. We give an explicit function $f : \{0,1\}^n \to \{0,1\}^n$ that requires at least $\Omega(\log^2 n)$ non-input gates when k = 2n/3. When the circuit is restricted to being layered and depth 2, we prove a lower bound of $n^{\Omega(1)}$ on the number of non-input gates. When the circuit is a formula with gates of fan-in k, we give a lower bound $\Omega(n^2/k \log n)$ on the total number of gates.

Our model is connected to some well known approaches to proving lower bounds in complexity theory. Optimal lower bounds for the Number-On-Forehead model in communication complexity, or for bounded depth circuits in AC_0 , or extractors for varieties over small fields

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would imply strong lower bounds in our model. On the other hand, new lower bounds for our model would prove new time-space tradeoffs for branching programs and impossibility results for (fan-in 2) circuits with linear size and logarithmic depth. In particular, our lower bound gives a different proof for a known time-space tradeoff for oblivious branching programs.

3.20 The power of a superlogarithmic number of players

Michael Saks (Rutgers University - Piscataway, US)

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 Main reference A. Chattopadhyay, M. Saks, "The Power of Super-logarithmic Number of Players," ECCC TR14-064, 2014.
 URL http://www.eccc.hpi-web.de/report/2014/064/

 \mathbf{L}

In the 'Number-on-Forehead' (NOF) model of multiparty communication, the input is a $k \times m$ boolean matrix A (where k is the number of players) and Player i sees all bits except those in the *i*-th row, and the players communicate by broadcast in order to evaluate a specified function f at A. We discover new computational power when k exceeds $\log m$. We give a protocol with communication cost poly-logarithmic in m, for block composed functions with limited block size. These are functions of the form $f \circ g$ where f is a symmetric b-variate function, and g is a kr-variate function and $f \circ g(A)$ is defined, for a $k \times br$ matrix to be $f(g(A^1), \ldots, g(A^b))$ where A^i is the *i*-th $k \times r$ block of A. Our protocol works provided that $k > 1 + \ln b + 2^r$. Ada, Chattopadhyay, Fawzi and Nguyen [1] previously obtained simultaneous and deterministic efficient protocols for composed functions with r > 1. Moreover, it is simultaneous, with vanishingly small error probability, if public coin randomness is allowed. The deterministic and zero-error version barely uses interaction.

References

 A. Ada, A. Chattopadhyay, O. Fawzi, and P. Nguyen. The NOF multiparty communication complexity of composed functions, International Colloquium on Automata, Programming and Languages (ICALP), pages 13–24, 2012.

3.21 Survey on recent progress on lower bounds for arithmetic circuits

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In the last few years there have been several exciting results related to depth reduction of arithmetic circuits and strong lower bounds for bounded depth arithmetic circuits. I will survey these results and highlight some of the main challenges and open directions in this area.

3.22 Pseudorandom generators with optimal seed length for non-boolean poly-size circuits

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 Joint work of Artemenko, Sergei; Shaltiel, Ronen
 Main reference S. Artemenko, R. Shaltiel, "Pseudorandom generators with optimal seed length for non-boolean poly-size circuits," in Proc. of the 46th Annual ACM Symp. on Theory of Computing (STOC'14), pp. 99–108, ACM, 2014.
 URL http://doi.acm.org/10.1145/2591796.2591846

A sampling procedure for a distribution P over $\{0,1\}^{\ell}$, is a function $C: \{0,1\}^n \longrightarrow \{0,1\}^{\ell}$ such that the distribution $C(U_n)$ (obtained by applying C on the uniform distribution U_n) is the "desired distribution" P. Let $n > r \ge \ell = n^{\Omega(1)}$. An *nb-PRG* (defined by Dubrov and Ishai (STOC 2006)) is a function $G: \{0,1\}^r \longrightarrow \{0,1\}^n$ such that for every $C: \{0,1\}^n \longrightarrow \{0,1\}^{\ell}$ in some class of "interesting sampling procedures", $C'(U_r) = C(G(U_r))$ is close to $C(U_n)$ in statistical distance.

We construct poly-time computable nb-PRGs with $r = O(\ell)$ (which is best possible) for poly-size circuits. Previous nb-PRGs of Dubrov and Ishai have $r = \Omega(\ell^2)$. We rely on the assumption that: there exists $\beta > 0$, and a problem L in $EE = DTIME(2^{O(n)})$ such that for every large enough n, nondeterministic circuits of size $2^{\beta n}$ that have NP- gates cannot solve L on inputs of length n. This assumption is a scaled nonuniform analogue of (the widely believed) $EXPT \neq \Sigma_2^{PT}$, and similar assumptions appear in various contexts in derandomization. The nb-PRGs of Dubrov and Ishai are based on very strong cryptographic assumptions, or alternatively, on non-standard assumptions regarding incompressibility of functions on random inputs.

When restricting to poly-size circuits $C : \{0,1\}^n \longrightarrow \{0,1\}^\ell$ with Shannon entropy $H(C(U_n)) \leq k$, for $\ell > k = n^{\Omega(1)}$, our nb- PRGs have r = O(k) which is best possible. The nb-PRGs of Dubrov and Ishai use seed length $r = \Omega(k^2)$ and require that the probability distribution of $C(U_n)$ is efficiently computable.

Our nb-PRGs follow from a notion of "conditional PRGs" which may be of independent interest. These are PRGs where $G(U_r)$ remains pseudorandom even when conditioned on a "large" event $\{A(G(U_r)) = 1\}$, for an arbitrary poly-size circuit A. A related notion was considered by Shaltiel and Umans (CCC 2005) in a different setup, and our proofs use ideas from that paper, as well as ideas of Dubrov and Ishai.

We also give an unconditional construction of a poly-time computable nb-PRGs for poly(n)-size, depth d circuits $C : \{0,1\}^n \longrightarrow \{0,1\}^\ell$ with $r = O(\ell \cdot \log^{d+O(1)} n)$. This improves upon the previous work of Dubrov and Ishai that has $r \ge \ell^2$. Our nb-PRGs can be implemented by a uniform family of poly-size constant depth circuits (with slightly larger, but still almost linear seed length). The nb-PRG of Dubrov and Ishai computes large parities and cannot be computed in poly-size and constant depth.

This result follows by adapting a recent PRG construction of Trevisan and Xue (CCC 2013) to the case of nb-PRGs, and implementing it by constant-depth circuits.

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3.23 Testing equivalence of polynomials under shifts

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 Joint work of Dvir, Zeev; Mendes de Oliveira, Rafael; Shpilka, Amir
 Main reference Z. Dvir, R. Oliveira, A. Shpilka, "Testing Equivalence of Polynomials under Shifts," in Proc. of the 41st Int'l Colloquium on Automata, Languages, and Programming (ICALP'14), LNCS, Vol. 8572, pp. 417–428, Springer, 2014; pre-print available from author's webpage.
 URL http://dx.doi.org/10.1007/978-3-662-43948-7_35
 URL http://www.cs.technion.ac.il/~shpilka/publications/DvirOliveiraShpilka14.pdf

Two polynomials $f, g \in \mathbb{F}[x_1, \ldots, x_n]$ are called shift-equivalent if there exists a vector $a \in \mathbb{F}^n$ such that the polynomial identity $f(x_1 + a_1, \ldots, x_n + a_n) \equiv g(x_1, \ldots, x_n)$ holds. Our main result is a new randomized algorithm that tests whether two given polynomials are shift equivalent. Our algorithm runs in time polynomial in the circuit size of the polynomials to which it is given black box access. This complements a previous work of Grigoriev who gave a deterministic algorithm running in time roughly n^d for degree d polynomials.

Our algorithm uses randomness only to solve instances of the Polynomial Identity Testing (PIT) problem. Hence, if one could derandomize PIT a derandomization of our algorithm would follow. This establishes an equivalence between derandomising shift-equivalence testing and derandomizing PIT.

3.24 A simple approach for construction of HSG for low-degree multivariate polynomials based on AG codes

Amnon Ta-Shma (Tel Aviv University, IL)

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Constructing pseudorandom generators for low degree polynomials has received a considerable attention in the past decade. Viola [CC 2009], following an exciting line of research, constructed a pseudorandom generator for degree d polynomials in n variables, over any prime field. The seed length used is $O(d \log n + d2^d)$, and thus this construction yields a non-trivial result only for $d = O(\log n)$. Bogdanov [STOC 2005] presented a pseudorandom generator with seed length $O(d^4 \log n)$. However, it is promised to work only for fields of size $\Omega(d^{10} \log^2 n)$. The work of Lu [CCC 2012], combined with that of Bogdanov, yields a pseudorandom generator with seed length $O(d^4 \log n)$ for fields of size $\Omega(d^{6+c})$ – independent of n, where c is an arbitrarily small constant.

In this work we show that for any d, a random sub-code (with a proper dimension) of any good algebraic geometry code, is a hitting set for degree d polynomials. By derandomizing this assertion, together with the work of Bogdanov, we obtain a construction of a pseudorandom generator for degree d polynomials over fields of size $\Omega(d^{12})$ – independent of n, and seed length $O(d^4 \log n)$.

Although quantitatively our result does not match Lu's parameters, our construction is clean mathematically and conceptually simple. We consider the proof technique to be the main contribution of this paper, and believe it will find other applications in complexity theory. In the heart of our proofs is a reduction from the problem of assuring independence between monomials to the much simpler problem of avoiding collisions over the integers. Our reduction heavily relies on the Riemann-Roch theorem.

3.25 Fixed-parameter parallelism

Till Tantau (Universität Lübeck, DE)

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 Joint work of Elberfeld, Michael; Stockhusen, Christoph; Tantau, Till
 Main reference C, Stockhusen, T. Tantau, "Completeness Results for Parameterized Space Classes," in Proc. of the 8th Int'l Symp. on Parameterized and Exact Computation (IPEC'13), LNCS, Vol. 8246, pp. 335–347, Springer, 2013.
 URL http://dx.doi.org/10.1007/978-3-319-03898-8_28

The talk presented some recent findings on fpt algorithms that can be parallelized. It was shown that the vertex cover problem can be solved in constant time using "fpt many processors" and that the feedback vertex set can be solved by an fpt algorithm that needs only slicewise logarithmic space, which in turn yields a parallel program. These results are part of a larger study of fixed parameter parallelism for which appropriate classes and models must be defined and their relationships investigated.

3.26 Counting the number of perfect matchings in *K*₅-free graphs

Thomas Thierauf (Hochschule Aalen, DE)

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Counting the number of perfect matchings in arbitrary graphs is a #P-complete problem. However, for some restricted classes of graphs the problem can be solved efficiently. In the case of planar graphs, and even for $K_{3,3}$ -free graphs, Vazirani showed that it is in NC². The technique there is to compute a *Pfaffian orientation* of a graph.

In the case of K_5 -free graphs, this technique will not work because some K_5 -free graphs do not have a Pfaffian orientation. We circumvent this problem and show that the number of perfect matchings in K_5 -free graphs can be computed in polynomial time, in fact in NC.

3.27 Approaches to bounding the exponent of matrix multiplication

Christopher Umans (CalTech, US)

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 Joint work of Umans, Chris; Alon, Noga; Cohn, Henry; Kleinberg, Bobby; Shpilka,Amir; Szegedy, Balazs
 Main reference H. Cohn, C. Umans, "Fast matrix multiplication using coherent configurations," arXiv:1207.6528v2
 [math.NA], 2012; pre-print also available from author's webpage.

 Main reference http://arxiv.org/abs/1207.6528v2

URL http://www.cs.caltech.edu/~umans/papers/CU12.pdf

We begin by describing the ideas behind the state-of-the-art bounds on omega, the exponent of matrix multiplication.

We then present the "group-theoretic" approach of Cohn and Umans as an alternative to these methods, and we generalize this approach from group algebras to general algebras. We identify adjacency algebras of coherent configurations as a promising family of algebras in the generalized framework. We prove a closure property involving symmetric powers of adjacency algebras, which enables us to prove nontrivial bounds on ω using commutative

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coherent configurations, and suggests that commutative coherent configurations may be sufficient to prove $\omega = 2$.

Along the way, we introduce a relaxation of the notion of tensor rank, called *s*-rank, and show that upper bounds on the *s*-rank of the matrix multiplication tensor imply upper bounds on the ordinary rank. In particular, if the "*s*-rank exponent of matrix multiplication" equals 2, then the (ordinary) exponent of matrix multiplication, ω , equals 2.

Finally, we will mention connections between several conjectures implying $\omega = 2$, and variants of the classical sunflower conjecture of Erdos and Rado.

No special background is assumed.

Based on joint works with Noga Alon, Henry Cohn, Bobby Kleinberg, Amir Shpilka, and Balazs Szegedy.

3.28 An interactive information odometer and applications

Omri Weinstein (Princeton University, US)

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Joint work of	Braverman, Mark; Weinstein, Omri
Main reference	M. Braverman, O. Weinstein, "An Interactive Information Odometer with Applications," ECCC
	TR14-047, 2014.
URL	http://eccc.hpi-web.de/report/2014/047/

We introduce a novel technique which enables two players to maintain an estimate of the internal information cost of their conversation in an online fashion without revealing much extra information. We use this construction to obtain new results about communication complexity and information- theoretically secure computation.

As a first corollary, we prove a strong direct product theorem for communication complexity in terms of information complexity: If I bits of information are required for solving a single copy of f under μ with probability 2/3, then any protocol attempting to solve n independent copies of f under μ^n using $o(n \cdot I)$ communication, will succeed with probability $2^{-\Omega(n)}$. This is the best one can hope for, as Braverman and Rao [FOCS '11] previously showed that $O(n \cdot I)$ communication suffice to succeed with probability $\sim (2/3)^n$.

We then show how the information odometer can be used to achieve information-theoretic secure communication between two untrusted parties: If the players' goal is to compute a function f(x, y), and f admits a protocol with information cost is I and communication cost C, then our odometer can be used to produce a "robust" protocol which: (i) Assuming both players are honest, computes f with high probability, and (ii) Even if one party is malicious, then for any $k \in \mathbb{N}$, the probability that the honest player reveals more than $O(k \cdot (I + \log C))$ bits of information to the other player is at most $2^{-\Omega(k)}$.

Finally, we outline a potential approach which uses our odometer as a proxy for braking state of the art interactive compression results: any progress on interactive compression in the regime where $I = O(\log C)$ will lead to new general compression results in all regimes. In particular, any improvement on the dependence on I in the $2^{O(I)}$ - compression result of Braverman [STOC '12] will lead to improved compression and new direct sum and product theorems in communication complexity.

3.29 Turnstile streaming algorithms might as well be linear sketches

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David P. Woodruff
Joint work of Li, Yi; Nguyen, Huy; Woodruff, David
Main reference Y. Li, H. L. Nguyen, D. P. Woodruff, "Turnstile streaming algorithms might as well be linear
cleated as: in Proc. of the 46th Annual ACM Sump. on Theory of Computing (STOC'14)

sketches," in Proc. of the 46th Annual ACM Symp. on Theory of Computing (STOC'14), pp. 174–183, ACM, 2014.
URL http://doi.acm.org/10.1145/2591796.2591812

Abstract: In the turnstile model of data streams, an underlying vector x in $\{-m, -m + 1, \ldots, m-1, m\}$ is presented as a long sequence of arbitrary positive and negative integer updates to its coordinates. A randomized algorithm seeks to approximate a function f(x) with constant probability while only making a single pass over this sequence of updates and using a small amount of space. All known algorithms in this model are linear sketches: they sample a matrix A from a distribution on integer matrices in the preprocessing phase, and maintain the linear sketch Ax while processing the stream. At the end of the stream, they output an arbitrary function of Ax. One cannot help but ask: are linear sketches universal?

In this work we answer this question by showing that any 1-pass constant probability streaming algorithm for approximating an arbitrary function f of x in the turnstile model can also be implemented by sampling a matrix A from the uniform distribution on $O(n \log m)$ integer matrices, with entries of magnitude poly(n), and maintaining the linear sketch Ax. Furthermore, the logarithm of the number of possible states of Ax, as x ranges over $\{-m, -m+1, \ldots, m-1, m\}^n$, plus the amount of randomness needed to store A, is at most a logarithmic factor larger than the space required of the space-optimal algorithm. Our result shows that to prove space lower bounds for 1-pass streaming algorithms, it suffices to prove lower bounds in the simultaneous model of communication complexity, rather than the stronger 1-way model. Moreover, the fact that we can assume we have a linear sketch with polynomially-bounded entries further simplifies existing lower bounds, e.g., for frequency moments we present a simpler proof of the $\tilde{\Omega}(n^{1-2/k})$ bit complexity lower bound without using communication complexity.

3.30 Growth rates of elementary symmetric polynomials

Amir Yehudayoff (Technion – Haifa, IL)

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 Joint work of Gopalan, Parikshit; Yehudayoff, Amir
 Main reference P. Gopalan, A. Yehudayoff, "Inequalities and tail bounds for elementary symmetric polynomials," ECCC TR14-019, 2014.

 URL http://eccc.hpi-web.de/report/2014/019/

We shall discuss the growth of elementary symmetric polynomials S_k , $k \in [n]$, over the reals. We shall see that if $|S_1(a)|, |S_2(a)|$ are small then $|S_k(a)|$ is small for all k. Some motivation to study this comes from pseudorandomness, and also from properties of real univariate polynomials.



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Report from Dagstuhl Seminar 14122

Verification of Cyber-Physical Systems

Edited by

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– Abstract -

Cyber-physical systems refer to a new genre of engineered systems consisting of a tight coupling between computation, communication and physical entities. The main focus of the seminar was to discuss issues related to the reliable development of cyber-physical systems by using formal verification. This is a multi-disciplinary area requiring collaboration between areas focusing discrete systems analysis and continuous systems analysis. To this end, the seminar brought together researchers working in the fields of formal methods, control theory and hybrid systems to identify and discuss potential issues and research questions which require collaboration between the communities. This report documents the program and the outcomes of Dagstuhl Seminar 14122 "Verification of Cyber-Physical Systems".

Seminar March 17–21, 2014 – http://www.dagstuhl.de/14122

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Introduction

Cyber-physical systems are systems in which there exists a tight coupling between computation, communication and control. The drastic reduction in the cost of sensing, actuating, computing and communicating technology has enabled the proliferation of this new genre of engineered systems in which a network of embedded processors interact tightly with the physical world to achieve complex functionalities. They have applications in a wide-range of systems spanning communication, infrastructure, energy, health-care, manufacturing, military, robotics and transportation.

Cyber-physical systems are believed to be the systems of the future with an impact on the engineering systems technology comparable to the impact the internet had on the information systems. Governments around the world have taken several initiatives to exploit this potential. The report of the US President's Council of Advisors on Science and Technology (PCAST) has placed Cyber-Physical Systems on the top of the priority list for federal research investment.



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The European Union has recognized the strategic importance of Embedded Computing Systems and has launched the ARTEMIS Joint Technology Initiative (JTI) as part of the FP7 program. Also, the latest European Commission Work Programme 2013 for Information and Communication technologies identifies this with the Objective ICT-2013.3.4 dedicated to Advanced Computing, Embedded and Control systems.

Cyber-Physical Systems have immense potential for a long-term impact on the society. At the same time, the unprecedented complexity arising due to the interleaving of the cyber and the physical components is overwhelming. On one hand, digital systems operate is a discrete manner, where computation and communication proceed in synchronization with the processor cycles. On the other hand, physical systems execute continuously in dense real-time. Hence, cyber-physical systems are complex systems exhibiting both discrete and continuous behaviors, and are networked and/or distributed with possibly humans in the loop. The grand challenge of the near future is the development of design methodologies and tools to cater to the development of reliable cyber-physical systems.

Model-based development has emerged as the de facto product development process in several domains including automotive and aeronautics. Here, the product development cycle begins with an abstract mathematical model of the system which is subject to rigorous analysis. The code is then generated from the model either automatically or manually. This enables early detection and correction of bugs which in turn results in the reduction of development costs and time, thereby providing companies with a competitive edge. However, the techniques used for analysis based on simulation of the mathematical models is still ad hoc, and does not provide the high level of reliability guarantees expected out of safetycritical CPS. Formal verification is an alternative approach which aims to provide a proof of correctness of the system. It is a promising technique for achieving the goal of developing high confidence cyber-physical systems.

Outcomes of the seminar

The seminar focused on the challenges in the application of formal methods towards verification of CPS. The seminar had a total of 28 participants with a mix of computer scientists and control theorists.

Tutorials

Given the cross disciplinary nature of the seminar, 6 tutorials were arranged on the following topics to provide a common ground to enable researchers with different backgrounds to communicate.

- 1. Simulation-Based Techniques for the Falsification of Cyber-Physical Systems
- 2. Verification of Automotive Engine Control
- 3. Formal Methods for Control Design
- 4. On Optimal and Reasonable Control in the Presence of Adversaries
- 5. Compositionality Results for Cardiac Cell Dynamics
- 6. Logic of Hybrid Games

Sessions

The following topics were identified as important issues in the application of formal verification to CPS. A separate session was dedicated to discuss the topics in the context of CPS.

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- 1. **Simulation based methods**: Application of simulation techniques for performing verification of CPS was discussed.
- 2. Using verification for control design: This session focused on the application of formal verification techniques such as those based on abstractions for control design.
- 3. **Foundation of CPS**: This session discussed the complexity and decidability of problems in verification and control of CPS.
- 4. **Applications**: This session discussed the methods and challenges in the verification of aircraft control, biological systems and multi-robot path planning.
- 5. **Abstractions**: This session discussed the issues regarding simplification techniques for scalable analysis of CPS.
- 6. Lyapunov based methods: This session discussed notions of stability and techniques for their analysis.
- 7. **Constraint solving**: Several verification problems can be formulated as constraint solving problems. This session discussed the challenges in constraint solving problems arising in CPS.
- 8. **Symbolic Verification**: This session discussed problems related to building efficient algorithms and tools for symbolic state-space exploration.

Research Directions

The seminar successfully fostered communication between computer scientist and control theorist. Some challenges and research directions were identified such as the need for the development of compositional reasoning of CPS with multiple components and lightweight analysis methods to boost scalability (such as using simulation for verification).

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3 Overview of Talks

3.1 Formal Methods for Dynamical Systems

Calin Belta (Boston University, Brookline, US, cbelta@bu.edu)

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Calin Belta

In control theory, "complex" models of physical processes, such as systems of differential equations, are usually checked against "simple" specifications, such as stability and set invariance. In formal methods, "rich" specifications, such as languages and formulae of temporal logics, are checked against "simple" models of software programs and digital circuits, such as finite transition graphs. With the development and integration of cyber physical and safety critical systems, there is an increasing need for computational tools for verification and control of complex systems from rich, temporal logic specifications.

The formal verification and synthesis problems have been shown to be undecidable even for very simple classes of infinite-space continuous and hybrid systems. However, provably correct but conservative approaches, in which the satisfaction of a property by a dynamical system is implied by the satisfaction of the property by a finite over-approximation (abstraction) of the system, have received a lot of attention in recent years. The focus of this talk is on discrete-time linear systems, for which it is shown that finite abstractions can be constructed through polyhedral operations only. By using techniques from model checking and automata games, this allows for verification and control from specifications given as Linear Temporal Logic (LTL) formulae over linear predicates in the state variables. The usefulness of these computational tools is illustrated with various examples.

3.2 Guided Search for Hybrid Systems

Sergiy Bogomolov (Universität Freiburg, DE, bogom@informatik.uni-freiburg.de)

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Hybrid systems represent an important and powerful formalism for modeling real-world applications such as embedded systems. A verification tool like SpaceEx is based on the exploration of a symbolic search space (the region space). As a verification tool, it is typically optimized towards proving the absence of errors. In some settings, e.g., when the verification tool is employed in a feedback-directed design cycle, one would like to have the option to call a version that is optimized towards finding an error path in the region space. A recent approach in this direction is based on guided search. Guided search relies on a cost function that indicates which states are promising to be explored, and preferably explores more promising states first. In this talk, we present two approaches to define and compute efficient cost functions. We develop our approaches on the top of the symbolic hybrid model checker SpaceEx which uses regions as its basic data structures.

In the first part of the talk, we introduce a box-based distance measure which is based on the distance between regions in the concrete state space. In the second part of the talk, we discuss an abstraction-based cost function based on pattern databases for guiding the reachability analysis. For this purpose, a suitable abstraction technique that exploits the flexible granularity of modern reachability analysis algorithms is introduced. We illustrate the practical potential of our approaches in several case studies.

3.3 Verification of Automotive Engine Control

Ken Butts (Toyota Technical Center, Ann Arbor, US, ken.butts@tema.toyota.com)

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In-vehicle control systems provide improved fuel consumption, emissions, vehicle dynamics and active safety features for the automotive customer. Attendant with these improvements is increased system and software complexity and thus, effective system verification and validation (V&V) is critical to assure dependability and reliability. Our group strives to apply advanced V&V to automotive engine control in a Model-Based Development (MBD) context.

In our work, we observe the following automotive control system characteristics:

- 1. The systems under control (i.e. the plant) are nonlinear and often hybrid in nature.
- 2. The systems are developed iteratively and thus, legacy designs play a prominent role.
- 3. Due to 1) and 2) above, the design synthesis process has been largely incremental and ad-hoc, though ISO26262 is yielding traceable-requirements-driven processes.
- 4. The de-facto standard control design development environment is Matlab/Simulink while the use of acausal methods (e.g. Modelica, Simscape, VHDL-AMS) for plant modeling is emerging.

In this talk, we outline how these observed characteristics motivate our research and present an overview of our current activities. We hope to learn new and effective ways to synthesize and verify in-vehicle control systems this workshop.

3.4 Flow*: Reachability Analysis of Non-Linear Hybrid Systems

Xin Chen (RWTH Aachen University, DE, xin.chen@cs.rwth-aachen.de)

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In this talk, we give a brief introduction of Flow* which is a reachability analysis tool for non-linear continuous and hybrid systems. Since the reachability problem on hybrid systems is not decidable, the tool computes an over-approximation which is represented by a finite set of Taylor models for the reachable set in bounded time horizon and number of jumps. The flowpipe/guard intersections are handled by the techniques of domain contraction and range over-approximation. They are extensions of the Taylor model method developed by Berz and Makino. To improve the performance of the tool, various techniques and heuristics are applied, and the effectiveness of them is demonstrated by several applications.

3.5 Conflict-Tolerant Specifications

Deepak D'Souza (Indian Institute of Science, Bangalore, IN, deepakd@csa.iisc.ernet.in)

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Deepak D'Souza

We consider the setting of a plant under the control of multiple independent controllers. Such systems are common in telecom, automobile, and other embedded domains. We propose

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a mechanism for specifying the behaviour of such controllers, called a conflict-tolerant specification, which is modular and gives us a compositional way of reasoning about the behaviour of the overall system. The theory is developed for discrete, timed, and hybrid system models.

This is joint work with Madhu Gopinathan, Prahlad Sampath, S. Ramesh, and others.

3.6 Parameter Synthesis for Biological Models

Thao Dang (VERIMAG, Gieres, FR, thao.dang@imag.fr)

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Parameter determination is an important task in the development of biological models. In this paper we consider parametric polynomial dynamical systems and address the following parameter synthesis problem: find a set of parameter values so that the resulting system satisfies a desired property. Our synthesis technique exploits the Bernstein polynomial representation to solve the synthesis problem using linear programming. We apply our framework to two case studies involving epidemic models.

3.7 Simulation-Guided Formal Analysis

Jyotirmoy V. Deshmukh (Toyota Technical Center, US, jyotirmoy.deshmukh@tema.toyota.com)

Industrial-scale control systems are often developed in the model-based development (MBD) paradigm. This typically involves capturing a 'plant model' that describes the dynamical characteristics of physical processes within the system, and a 'controller model,' which is a block-diagram-based representation of the software used to regulate the plant behavior. In practice, plant models and controller models are highly complex; typical features include highly nonlinear and hybrid dynamics, dynamics involving delay differential equations, lookup tables storing pre-computed values, several levels of design-hierarchy, and design-blocks that operate at different frequencies. Design validation in the industry often takes the form of extensive testing on various platforms such in-vehicle testing, hardware-in-the-loop simulations, and software/model-in-the-loop simulations. The Simulink modeling framework (from the MathWorks) has become the de facto standard across industry for describing closed-loop plant + controller MBD designs. The key feature of this framework is a highfidelity simulation tool, routinely used by control designers to experimentally validate their controller designs. In effect, we have a situation where designers have access to a wide range of methods that can perform extensive (but not exhaustive) simulations of a system. On the other end of the spectrum, the hybrid systems community has been developing a number of formal verification techniques that provide sound (but conservative and hence inaccurate) results. We consider the question: 'What can we "formally" accomplish if all we have is the ability to simulate a system?' As a tentative answer to this question, we suggest a paradigm called "Simulation-guided Formal Analysis". Such a framework could include key components such as procedures to perform inductive learning from simulations, procedures to check whether the information learned from simulations is consistent with all

behaviors of the model being simulated, and techniques that focus on best-effort verification with probabilistic completeness guarantees. As an instance of this paradigm, we present a technique to discover Lyapunov functions for nonlinear and hybrid systems from simulation data using linear programming techniques, global optimization tools and nonlinear SMT solvers.

3.8 Descending MTL Robustness

Georgios Fainekos (Arizona State University, Tempe, US, fainekos@asu.edu)

Metric Temporal Logic (MTL) specifications can capture complex state and timing requirements. Given a nonlinear dynamical system and an MTL specification for that system, our goal is to find a trajectory that violates or satisfies the specification. This trajectory can be used as a concrete feedback to the system designer in the case of violation or as a trajectory to be tracked in the case of satisfaction. The search for such a trajectory is conducted over the space of initial conditions, system parameters and input signals. We convert the trajectory search problem into an optimization problem through MTL robust semantics. Robustness quantifies how close the trajectory is to violating or satisfying a specification. Starting from some arbitrary initial condition and parameter and given an input signal, we compute a descent direction in the search space, which leads to a trajectory that optimizes the MTL robustness. This process can be iterated to reach local optima (min or max). We demonstrate the method on examples from the literature.

3.9 Reachability in Space-Time for Piecewise Affine Dynamics

Goran Frehse (Université Joseph Fourier – Verimag, FR, goran.frehse@imag.fr)

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Symbolic simulation, also referred to as reachability analysis, can complement trajectorybased analysis techniques to ensure a dynamic system satisfies a safety property. Instead of computing a sequence of points on a single trajectory, we compute a sequence of sets that covers all possible trajectories of the system. Computing with sets allows us to use conservative over-approximations and take into account various kinds of nondeterminism in the plant and the controller. While computing with sets is inherently costly and has long been restricted to toy problems, recent advances based on implicit ("lazy") set representations have made symbolic simulation applicable to linear ODEs with hundreds of variables. In this talk, we present a semi-template data structure, consisting of a set of piecewise linear scalar functions, that is used to approximate the nonconvex reachable set over time. It represents a (usually large) set of convex polyhedra in space-time in a compact manner. A number of operations, such as affine transformations, convex hull, and simplification, can be carried out very efficiently in this representation, and the resulting approximation error can be measured accurately. This has lead to gains in both accuracy and performance, and opens up new domains of application for symbolic simulation. The approach has been implemented on the verification platform SpaceEx developed at Verimag.

3.10 **Compositionality Results for Cardiac Cell Dynamics**

Radu Grosu (Vienna University of Technology, Wien, AT, radu.grosu@tuwien.ac.at)

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Joint work of Islam, Ariful; Murthy, Abhishek; Girard, Antoine; Smolka, Scott A.; Grosu, Radu

Main reference A. Islam, A. Murthy, A. Girard, S. A. Smolka, R. Grosu, "Compositionality results for cardiac cell dynamics," in Proc. of the 17th Int'l Conf. on Hybrid Systems: Computation and Control, pp. 243–252, ACM, 2014.

URL http://dx.doi.org/10.1145/2562059.2562138

By appealing to the small-gain theorem of one of the authors (Girard), we show that the 13-variable sodium-channel component of the IMW cardiac-cell model (Iyer-Mazhari-Winslow) can be replaced by an approximately bisimilar, 2-variable HH-type (Hodgkin-Huxley) abstraction. We show that this substitution of (approximately) equals for equals is safe in the sense that the approximation error between sodium-channel models does not get amplified by the feedback-loop context in which it is placed. To prove this feedbackcompositionality result, we exhibit quadratic-polynomial, exponentially decaying bisimulation functions between the IMW and HH-type sodium channels, and also for the IMW-based context in which these sodium-channel models are placed. These functions allow us to quantify the overall error introduced by the sodium-channel abstraction and subsequent substitution in the IMW model. To automate the computation of the bisimulation functions, we employ the SoS-Tools optimization toolbox. Our experimental results validate our analytical findings. To the best of our knowledge, this is the first application of approximately bisimilar, feedbackassisting, compositional reasoning in biological systems.

3.11 Two Approaches to Applying Verification to Control Design

Bruce Krogh (Carnegie Mellon University, Pittsburgh, US, krogh@ece.cmu.edu)

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The standard application of verification tools to control design is to design the controller and then verify properties of the closed-loop system. We are investigating an alternative approach in which verification is used first to establish the safety of a nondeterministic controller. This becomes an envelope which can then be used either as a constraint in a control design process, or it can be used to verify a designed controller. One advantage of this second approach is that the envelope is a condition on only the input- output behavior of the controller rather than a condition on the closed-loop behavior.

3.12 Finite-time Lyapunov functions

Mircea Lazar (Eindhoven University of Technology, Eindhoven, NL, m.lazar@tue.nl)

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Lyapunov functions are essential tools for verifying stability of real-life systems, such as modern cars or power systems. However, choosing a Lyapunov function candidate and then verifying if such a function exists is a very complex process. In this work we study a

Rupak Majumdar, Richard M. Murray, and Pavithra Prabhakar

relaxation of the Lyapunov function concept, termed finite-time Lyapunov function and we demonstrate that it can lead to scalable stability analysis tests for linear and switched linear systems (with state dependent switching). The analysis is carried out in the discrete-time setting. Examples from power systems will be used to demonstrate the applicability of the developed stability tests. A preliminary approach to the verification of stability for general nonlinear discrete-time systems based on finite-time Lyapunov functions is also presented.

3.13 On Optimal and Reasonable Control in the Presencve of Adversaries

Oded Maler (VERIMAG, Gieres FR, oded.maler.imag.fr)

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This work constitutes a sketch of a unified framework for posing and solving problems of optimal control in the presence of uncontrolled disturbances. After laying down the general framework we look closely at a concrete instance where the controller is a scheduler and the disturbances are related to uncertainties in task durations.

3.14 Scalable Techniques for Viability Kernels and Safe Control Synthesis in Linear Time Invariant Systems

Ian Mitchell (University of British Columbia, Vancouver, CA, mitchell@cs.ubc.ca)

We present a connection between the viability kernel and maximal reachable sets. Current numerical schemes that compute the viability kernel suffer from a complexity that is exponential in the dimension of the state space. In contrast, extremely efficient and scalable techniques are available that compute maximal reachable sets. We show that under certain conditions these techniques can be used to conservatively approximate the viability kernel for possibly high-dimensional systems. We demonstrate three implementations using different set representations, and several examples. One of these set representations can be used to generate a nondeterministic hybrid control automaton which synthesizes a permissive but safe feedback control signal.

3.15 Verification of Nonlinear Models with Modular Annotations

Sayan Mitra (University of Illinois at Urbana-Champaign, US, mitras@illinois.edu)

In this talk I will give a overview of techniques for obtaining bounded time invariant proofs from simulations and model annotations. We use annotations called discrepancy functions that quantify the continuity of trajectories starting from neighboring states. Then, I will present a modular technique for simulation-based bounded verification for nonlinear dynamical systems.

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We introduce the notion of input-to-state discrepancy of each subsystem A_i in a larger nonlinear dynamical system A which bounds the distance between two (possibly diverging) trajectories of A_i in terms of their initial states and inputs. Using the IS discrepancy functions, we construct a low dimensional deterministic dynamical system $M(\delta)$. For any two trajectories of A starting δ distance apart, we show that one of them bloated by a factor determined by the trajectory of M contains the other. Further, by choosing appropriately small δ 's the over-approximations computed by the above method can be made arbitrarily precise. Using the above results we develop a sound and relatively complete algorithm for bounded safety verification of nonlinear ODEs with modular annotations. Our preliminary experiments with a prototype implementation of the algorithm show that the approach can be effective for verification of large nonlinear models.

3.16 Challenges in Verification of Hybrid Systems for Aerospace Applications

Richard M. Murray (California Institute of Technology, US, murray@cds.caltech.edu)

Flight critical subsystems in aerospace vehicles must achieve probability of failure rates of less than 1 failure in 10⁹ flight hours (i.e. less than 1 failure per 100,000 years of operation). Systems that achieve this level of reliability are hard to design, hard to verify, and hard to validate, especially if software is involved. In this talk I describe some of the challenges in design of vehicle management systems for aerospace applications and some of the opportunities for the use of formal methods for verification and synthesis.

3.17 Logic of Hybrid Games

André Platzer (Carnegie Mellon University, Pittsburgh, US, aplatzer@cs.cmu.edu)

Hybrid systems model cyber-physical systems as dynamical systems with interacting discrete transitions and continuous evolutions along differential equations. They arise frequently in many application domains, including aviation, automotive, railway, and robotics. This talk studies hybrid games, i.e. games on hybrid systems combining discrete and continuous dynamics. Unlike hybrid systems, hybrid games allow choices in the system dynamics to be resolved adversarially by different players with different objectives.

This talk describes how logic and formal verification can be lifted to hybrid games. The talk describes a logic for hybrid systems called differential game logic dGL. The logic dGL can be used to study the existence of winning strategies for hybrid games, i.e. ways of resolving the player's choices in some way so that he wins by achieving his objective for all choices of the opponent. Hybrid games are determined, i.e. one player has a winning strategy from each state, yet their winning regions may require transfinite closure ordinals. The logic dGL, nevertheless, has a sound and complete axiomatization relative to any expressive logic. Separating axioms are identified that distinguish hybrid games from hybrid systems. Finally, dGL is proved to be strictly more expressive than the corresponding logic of hybrid systems.

3.18 Algorithmic Verification of Stability of Hybrid Systems

Pavithra Prabhakar (IMDEA Software Institute, ES, pavithra.prabhakar@imdea.org)

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We focus on the verification of stability of hybrid systems. Stability is a fundamental property in control system design and captures the notion that small perturbations to the initial state or input to the system result in only small variations in the eventual behavior of the system. We present foundations and concrete techniques for abstraction based stability analysis. In contrast to the well-known methods for automated verification of stability based on Lyapunov functions, which are deductive, we present algorithmic techniques for stability analysis.

3.19 Highlights on Recent Progresses in Quantitative Games

Jean-François Raskin (Université Libre de Bruxelles, BE, jraskin@ulb.ac.be)

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In this talk, I have summarized the results obtained in the three following papers:

- The Complexity of Multi-Mean-Payoff and Multi-Energy Games. In mean-payoff games, the objective of the protagonist is to ensure that the limit average of an infinite sequence of numeric weights is nonnegative. In energy games, the objective is to ensure that the running sum of weights is always nonnegative. Multi-mean-payoff and multi-energy games replace individual weights by tuples, and the limit average (resp. running sum) of each coordinate must be (resp. remain) nonnegative. These games have applications in the synthesis of resource-bounded processes with multiple resources. We prove the finite-memory determinacy of multi-energy games and show the inter-reducibility of multimean-payoff and multi-energy games for finite-memory strategies. We also improve the computational complexity for solving both classes of games with finite-memory strategies: while the previously best known upper bound was EXPSPACE, and no lower bound was known, we give an optimal coNP-complete bound. For memoryless strategies, we show that the problem of deciding the existence of a winning strategy for the protagonist is NP-complete. Finally we present the first solution of multi-meanpayoff games with infinite- memory strategies. We show that multi-mean-payoff games with mean-payoff- sup objectives can be decided in NP and coNP, whereas multi-mean-payoff games with mean-payoff-inf objectives are coNP-complete.
- Meet Your Expectations With Guarantees: Beyond Worst-Case Synthesis in Quantitative Games. We extend the quantitative synthesis framework by going beyond the worst-case. On the one hand, classical analysis of two-player games involves an adversary (modeling the environment of the system) which is purely antagonistic and asks for strict guarantees. On the other hand, stochastic models like Markov decision processes represent situations where the system is faced to a purely randomized environment: the aim is then to optimize the expected payoff, with no guarantee on individual outcomes. We introduce the beyond worst-case synthesis problem, which is to construct strategies that guarantee some quantitative requirement in the worst-case while providing an higher expected value against a particular stochastic model of the environment given as input. This problem is relevant to produce system controllers that provide nice expected performance in the

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everyday situation while ensuring a strict (but relaxed) performance threshold even in the event of very bad (while unlikely) circumstances. We study the beyond worst-case synthesis problem for two important quantitative settings: the mean-payoff and the shortest path. In both cases, we show how to decide the existence of finite-memory strategies satisfying the problem and how to synthesize one if one exists. We establish algorithms and we study complexity bounds and memory requirements.

Looking at Mean-Payoff and Total-Payoff through Windows. We consider two-player games played on weighted directed graphs with mean- payoff and total-payoff objectives, two classical quantitative objectives. While for single-dimensional games the complexity and memory bounds for both objectives coincide, we show that in contrast to multi-dimensional mean-payoff games that are known to be coNP-complete, multi-dimensional total-payoff games are undecidable. We introduce conservative approximations of these objectives, where the payoff is considered over a local finite window sliding along a play, instead of the whole play. For single dimension, we show that (i) if the window size is polynomial, deciding the winner takes polynomial time, and (ii) the existence of a bounded window can be decided in NP \cap coNP, and is at least as hard as solving mean-payoff games. For multiple dimensions, we show that (i) the problem with fixed window size is EXPTIME-complete, and (ii) there is no primitive-recursive algorithm to decide the existence of a bounded window.

3.20 Analysis and Synthesis of CPS using EF-SMT

Harald Ruess (fortiss GmbH – München, DE, harald.ruess@gmail.com)

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The design of cyber-physical systems is challenging in that it includes the analysis and synthesis of distributed and embedded real-time systems for controlling, often in a nonlinear way, the environment. We address this challenge with EFSMT, the exists-forall quantified first-order fragment of propositional combinations over constraints (including nonlinear arithmetic), as the logical framework and foundation for analyzing and synthesizing cyber-physical systems. We demonstrate the expressiveness of EFSMT by reducing a number of pivotal verification and synthesis problems to EFSMT. Exemplary problems include synthesis for robust control via BIBO stability, Lyapunov coefficient finding for nonlinear control systems, distributed priority synthesis for orchestrating system components, and synthesis for hybrid control systems. We are also proposing an algorithm for solving EFSMT problems based on the interplay between two SMT solvers for respectively solving universally and existentially quantified problems. This algorithms builds on commonly used techniques in modern SMT solvers, and generalizes them to quantifier reasoning by counterexample-guided constraint strengthening. The EFSMT solver uses Bernstein polynomials for solving nonlinear arithmetic constraints.

3.21 Compositional Synthesis of Multi-Robot Motion Plans via SMT Solving

Indranil Saha (University of California – Berkeley, US, saha.indra@gmail.com)

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We present a constraint based compositional motion planning framework for multi-robot systems. In this framework, the runtime behavior of a group of robots is specified using a set of safe LTL properties. Our method relies on a library of motion primitives that provides a set of controllers to be used to control the behavior of the robots in different configurations. Using the closed loop behavior of the robots under the action of different controllers, we formulate the motion planning problem as a constraint solving problem and use an off-the-shelf satisfiability modulo theories (SMT) solver to solve the constraints and generate trajectories for the individual robot. Our approach can also be extended to synthesize optimal cost trajectories where optimality is defined with respect to the available motion primitives. Experimental results show that our framework has potential to solve complex motion planning problems in the context of multi-robot systems.

3.22 Simulation-Based Techniques for the Falsification of Cyber-Physical Systems

Sriram Sankaranarayanan (University of Colorado Boulder, US, srirams@colorado.edu)

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The tutorial will describe some of the major ideas on the use of simulations to automate the discovery of property violations in CPS designs. As model-based design is increasingly prevalent, frameworks such as Simulink(tm)/Stateflow(tm), SCADE(tm) and Modelica(tm) are becoming de-facto standards for designing and verifying CPS. Simulation, therefore, is an attractive approach for finding defects in designs including violations of reachability and stability specifications. Our review will highlight some of the major simulation approaches including ideas from robotic motion planning (e.g. Rapid Exploration of Random Trees, Probabilistic Roadmaps), optimization/optimal control (e.g., robustness-guided falsification, trajectory optimization, multiple shooting methods), and the relation with well-known symbolic approaches used in formal verification (e.g., bounded-model checking, abstractionrefinement). We will briefly describe some of the successes of these techniques and open problems including "simulation explosion" and the need for formal underpinnings for these techniques. We will conclude by describing some attempts at solving these open problems.

3.23 Certified-by-design control of systems over finite alphabets

Danielle Tarraf (Johns Hopkins University, US, dtarraf@jhu.edu)

In this talk, I propose a theoretical and algorithmic framework for synthesizing certified-bydesign control systems using simple components with limited information processing and memory capabilities. Specifically, I consider a setup in which plants interact with their controllers via fixed discrete alphabets, and in which controller memory is finite. I describe a set of analysis tools for systems over finite alphabets and a set of synthesis tools for finite state models. A common theme is the use of input-output constraints to describe system properties of interest. I then propose a control-oriented notion of finite state approximation compatible with these analysis and synthesis tools, I present constructive algorithms for generating these approximations, and I demonstrate their use in simple examples. Finally, I discuss some aspects of state estimation under finite alphabet and memory constraints.

3.24 EF-SMT

Ashish Tiwari (SRI International – Menlo Park, US, tiwari@csl.sri.com)

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Many problems in verification and synthesis of cyber-physical systems can be reduced to deciding formulas of the form exists-forall-F, where F is a quantifier-free formula in some combination of theories. Satisfiability modulo theory (SMT) solvers decide satisfiability of formulas of the form exists-F, whereas Exists-Forall-SMT (EF-SMT) solvers decide formulas of the form exists-forall-F.

We show how a generic EF-SMT solver can be built over an SMT solver, much in the same way as an SMT solver is built over a Boolean SAT solver. We also briefly describe a new procedure for solving EF and E problems over a fragment of the theory of nonlinear real arithmetic. The new procedure can be viewed as a generalized SAT solver.

3.25 Stability of Linear Autonomous Systems Under Regular Switching Sequences

Mahesh Viswanathan (University of Illinois at Urbana-Champaign, US, vmahesh@illinois.edu)

A linear autonomous system under regular switching sequences is constructed by viewing the dynamic modes of a linear autonomous switched system as the alphabet of a Muller Automaton with accepting conditions on transitions instead of states and restricting the switching sequences of dynamic modes by the language generated by the automaton. The asymptotic stability of this system, defined as regular asymptotic stability, generalizes two well-known definitions of stability of linear autonomous switching system namely absolute asymptotic stability and shuffle asymptotic stability. We also extend the definitions of

Rupak Majumdar, Richard M. Murray, and Pavithra Prabhakar

stability to their robust versions. We prove that absolute asymptotic stability, robust absolute asymptotic stability robust shuffle asymptotic stability are equivalent to uniform exponential stability. In addition, by using Kronecker product, we convert a regular stability problem into the conjunction of shuffle asymptotic stability problems and prove that a robust regular stability problem is equivalent to the conjunction of several robust absolute asymptotic stability problems or uniformly exponential stability problems.



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Computational Models of Cultural Behavior for Human-Agent Interaction

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— Abstract

From March 23 2014 to March 28, the seminar "Computational Models of Cultural Behavior for Human-Agent Interaction" held in Schloss Dagstuhl – Leibniz Center for Informatics. During the seminar, an interdisciplinary group of researchers explored and discussed theories and techniques for computational models of culture as part of virtual human simulations. Culturally-sensitive agents do not only improve the acceptance of man-machine interfaces by adapting their verbal and non-verbal behavior to the user's assumed cultural background. They also bear enormous potential for a rapidly growing number of ICT-based language and cultural training scenarios that make use of role-play with virtual characters. The seminar brought together researchers with an interdisciplinary background that profited from each other's perspective and explored challenges for the future.

Seminar March 23-28, 2014 - http://www.dagstuhl.de/14131

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1 Executive Summary

Elisabeth André Ruth Aylett Gert Jan Hofstede Ana Paiva

The seminar was the first international meeting on computational models of culture. The gathering of a multi-disciplinary team of experts with a background in intelligent virtual agents, human-computer interaction and cultural theories provided us with a lot of inspirations for future research projects. We did not only identify relevant topics for a roadmap on computational models of culture, but also worked out a number of intriguing applications for cultural agents.



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In order to exploit the momentum and enthusiasm generated by the seminar, we discussed some ideas for community building. We plan to organize a follow-up Dagstuhl seminar in about two or three years. However, some participants felt they would not like to wait for such a long time and spontaneously decided to have an additional workshop on Cultural Models for Intelligent Virtual Agents at the Fourteenth International Conference on Intelligent Virtual Agents (IVA 2014) in Boston this year. Furthermore, we discussed the edition of a book and/or a special issue. In addition, we talked about possibilities to share and distribute corpora to support comparative studies of culture-specific behaviors.

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3 Background and Topic of the Seminar

Research on intelligent virtual agents has established itself as a major field of research in computer science with a dedicated annual international conference: the International Conference on Intelligent Virtual Agents (IVA). In the last twenty years, significant advances have been made in enhancing the believability of such agents by endowing them not only with multimodal conversational behaviors, but also tailoring their behavior to emotional and/or personality. However, few researchers have taken up the challenge of modeling the influences culture has on behavior so far even though there is clear empirical evidence that the culture a virtual agent reflects strongly influences how it is accepted by a human user.

For the design of virtual agents, the challenge has been identified, but realizations are often superficial concentrating on avatar appearance for specific cultural groups. De Rosis, Pelachaud and Poggi illustrate this problem with their survey of the Microsoft Agents web site, which shows that the appearances as well as the animations of the characters are almost all based on western cultural norms. They only found four non-western style agents, which moreover exhibited only a reduced set of animations. Agent style can in turn safely be taken as a proxy for agents' implicit rules of behavior linked to culture. Apart from imposing western cultural standards on all users, the danger lies in a very low acceptance of such agents by users with different cultural backgrounds.

The design of agents that reflect a particular cultural background requires computational models that allow the explicit representation of cultural parameters impacting the behavior of the agents in the same way as theories of cognitive appraisal and coping behavior underlie emotional parameters in affective agent architectures. However, research into agent architectures that include cultural factors in the virtual agents' internal knowledge and reasoning is still quite new. Basically, there are two approaches to implement computational models of culture in the Autonomous Agent and Multi-Agent community:

Data-driven approaches to computational models of culture

In the data-driven approach, computational models of culture are based on annotated multimodal recordings of existing cultures from which culture-specific behavior profiles are learnt. A prominent example includes the German-Japanese project CUBE-G project funded by the German Science Foundation (DFG) and the Japan Society for the Promotion of Science (JSPS) (http://www.hcm-lab.de/projects/cube-g/). In this project, a corpus of multimodal behavior was collected under standardized conditions for three prototypical scenarios in two cultures, Germany and Japan. For this corpus, a statistical analysis was performed highlighting differences between German and Japanese speakers in the use of gestures and postures, communication management, choice of topics etc. The advantage of data-driven computational models of culture lies in their empirical foundation. However, the collection and annotation of cross-cultural corpora is extremely time-consuming and usually requires a multi-national effort. Furthermore, there is the danger that the model derived from the corpora is incomplete resulting into an inconsistent culture-specific behavior of the agents. A third drawback is that the data is hard to generalize to other settings, for lack of a causal model. Finally, it is not obvious how to map statistical behavior data onto computational models even though first attempts have been made in the area of intelligent virtual agents using machine learning approaches.

Computational models of culture as extension of agent mind architectures

Another approach to implement computational models of culture is to start from existing multi-agent architectures and extend them to allow for culture-specific adaption of goals, beliefs and plans. One of the earliest and most well-known systems is the Tactical Language

System (http://www.tacticallanguage.com/) which has formed the basis of a variety of products for language and culture training by Alelo Inc. Tactical Language is based on architecture for social behavior called Thespian that implements a version of Theory of Mind. This feature is required in cultural agents that model collectivistic cultures where people care a lot about the consequences their actions have on others. More recent systems have been developed within the European projects eCIRCUS (http://www.e-circus.org/) and eCUTE (http://ecute.eu/) and extended an agent mind architecture called FAtiMA by representations of the Hofstede cultural dimension values for the culture of the character, cultural specific symbols, culturally specific goals and needs, and the rituals of the culture. While a more formal approach to cultural models is very well suited for the implementation of synthetic cultures and usually ensures a higher level of consistency than the data-driven approach, it is not grounded in real data and thus may not completely realistically simulate existing cultures. Another limitation is that it is difficult to decide which specific gestures and behaviors to choose for externalizing the goals and needs generated in the agent minds.

In an increasingly globalized world, cultural sensitivity, awareness and understanding has become a major factor of success. As more and more companies do business in other cultures, there is large demand for ICT-based language and culture training systems. Cultural agents have been used as part of social simulations, language and culture training tools.

The seminar has brought together a multi-disciplinary team of experts with a background in intelligent virtual agents, human-computer interaction and cultural theories. In the following, we describe the organization of the seminar, the topics and results of the break out groups as well as plans for future steps.

4 Organization of the Seminar

The seminar was a balanced combination of Pecha Kucha style introductory presentations, seed talks by leading experts, poster and demo sessions and break out groups (see seminar program shown in Figure 1).

Six leading experts were invited to give a seed talk in order to provide us with inspirations for the break out groups. Apart from five colleagues with an academic background, we also invited one representative from industry to convey his perspective on the field.

We had two rounds of break out groups. In the first round of break out groups the focus was on theories, architectures, data, evaluation and applications. In the second round of break out groups we discussed specific applications for cultural agents to concretize our ideas.

A particular highlight of the seminar was the evening program with social activities focusing on the topic of the seminar. We organized a cultural evening where participants presented artifacts from their own culture (stories, songs, dances, food, drinks etc.). In addition, we scheduled an evening where we formed several groups to play cultural games (Barnga, Bafa Bafa). These events did not only help break the ice between participants, but also contributed to a better understanding on the role of culture in social interactions and provided us with a lot of inspirations for the implementation of cultural models.

	Monday	Tuesday	Wednesday	Thursday	Friday
Session1	Welcome/Intro (Ruth) 60 second intros (All)	Sarit Kraus: When Is it Beneficial to Develop Culture Sensitive Negotiation Agents?	David Traum: Models of Culture for Virtual Human Conversation	Lewis Johnson: Effective Cultural Models: An Industry Perspective	Wrap-up
	Coffee	Coffee	Coffee	Coffee	Coffee
Session2	Goals (Ruth) Ideas Gathering (All)	Break-out sessions	Justine Cassel: Dyadic Models of Cultural Interaction	Break-out sessions	Informal discussion
12.15	Lunch	Lunch	Lunch	Lunch	Lunch
Session3	Gert Jan Hofstede: Robot and agent culture	Jens Allwood: Cultural perspectives on communication	Social outing	Break-out sessions	DEPART
	Coffee	Coffee	Coffee	Coffee	
Session4	Demos/posters	Break-out sessions	Social outing	Break-out sessions	
18.00	Dinner	Dinner	Dinner	Dinner	
Evening	Cultural Training Games: Barnga, Bafa Bafa	This is Us: Participants present artefacts from their own culture (stories, songs, dances, food, drinks etc.)	Meal elsewhere	This is Us Again: Spontaneous talks, anecdotes about scientific cultures, examples of cultural misunderstandings etc. Presentation of additional cultural items	

Figure 1 Seminar Program

5 Overview of Talks

5.1 Robot and agent culture

Gert Jan Hofstede (Wageningen University, NL)

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 Gert Jan Hofstede

 Main reference
 G. Hofstede, G. J. Hofstede, M. Minkov, "Cultures and Organizations, Software of the Mind," Revised and expanded 3rd Edition, ISBN 978-0071664189, McGraw Hill, 2010.

First, the lecture addressed the question "Do we need agents and robots to have culture?" The answer is yes, because they have to mimic human social behaviour, as well as to meet, instruct, and serve people. Second, the lecture gives a broad introduction to culture. People create culture wherever they are together. The deepest level, that of unconscious values, is formed in childhood, and has the most impact on our adult social behaviours. Societies tend to have shared values that remain fairly stable over time, even if individuals and sub-groups differ and practices change continually. A limited set of dimensions of value can be used to compare societal cultures. The dimensions proposed in [1] are used as the main example.

Third, the lecture touches on how societal culture could be modelled. It makes the argument that agents need to have a generic social awareness before they can acquire culture. Such a generic model could be based on the work of various social scientists. The status-power model of Theodore Kemper [3] is taken as an example. On top of such a model, cultural variations can be given to the agents. The model of social importance dynamics [2], itself based on Kemper, is used to show how this could be done.

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5.2 When Is it Beneficial to Develop Culture Sensitive Negotiation Agents?

Sarit Kraus (Bar-Ilan University – Haifa, IL)

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C Sarit Kraus
Joint work of Gal, Ya'akov; Haim, Galit; Rosenfeld, Avi
URL http://www.cs.biu.ac.il/~sarit/pub.html

Negotiation and persuasion are tools for social influence that are endemic to human interaction, from personal relationships and business partnerships to political debate. The inclusion of people presents novel problems for the design of automated agents' negotiation and persuasion strategies. People do not adhere to the optimal, monolithic strategies that can be derived analytically. Their negotiation behavior is affected by a multitude of social and psychological factors. In particular, people's cultural background has been shown to affect the way they reach agreements in negotiation and how they fulfill these agreements. We have shown that combining machine learning techniques for opponent modeling with human behavioral models and formal decision making approaches while taking culture into consideration enable agents to interact well with people. I will present a few culture sensitive agents. The KBagent and NegoChat agent negotiate with people in multi-issue negotiation settings. They were evaluated in the US and Israel. Then, we will discuss Colored Trails agents, PURB and PAL, that had been designed for repeated bilateral negotiation when agreements are not enforceable. They were evaluated in Israel, USA and Lebanon. We will also present an equilibrium agent for 3 players CT game that was evaluated in China, Israel and the USA. We will also report experiments on corruption game comparing people behavior in Israel, USA and China. We conclude by discussing the advantages and challenges of developing culture sensitive agents.

PURB models and adapts its behavior to the individual traits exhibited by its negotiation partner. The agent's decision-making model combines a social utility function that represents the behavioral traits of the other participant with a rule-based mechanism that uses the utility function to make decisions in the negotiation process. PURB negotiated with human subjects in the U.S. and Lebanon in situations that varied the dependency relationships between participants at the onset of the negotiation. There was no prior data available about the way people would respond to different negotiation strategies in these two countries. Results showed that people from Lebanon and the USA played differently. In particular, subjects in Lebanon were significantly more reliable than subjects from the USA. PURB was able to adopt a different negotiation strategy to each country. Its average performance across both countries was equal to that of people. However, the agent outperformed people in the United States, because it learned to make offers that were likely to be accepted by people while at the same time being more beneficial to the agent. In contrast, the agent was outperformed by people in Lebanon because it adopted a high reliability measure which allowed people to take advantage of it. The Personality Adaptive Learning (PAL) agent, which negotiates proficiently with people from different cultures; and the Social agent for Advice Provision (SAP) that influences human's decision in settings such as the route selection applications. These agents were evaluated in extensive experiments including people from three countries.

Acknowledgements. Sarit Kraus is also affiliated with UMIACS. This work was supported in part by ERC grant #267523 and the U.S. Army Research Laboratory and the U.S. Army Research Office under Grant number W911NF-08-1-0144.

5.3 On some challenges and features of a theory of intercultural communication

Jens Allwood (University of Göteborg, SE)

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- Main reference J. Allwood, "Tvärkulturell Kommunikation," in J. Allwood (ed.), Tvärkulturell kommunikation, Papers in Anthropological Linguistics 12, 1985; englisch translation available. URL http://sskkii.gu.se/jens/publications/docs001-050/041.pdf
- URL http://sskkii.gu.se/jens/publications/docs001-050/041E.pdf Main reference J. Allwood, E. Ahlsén, "Multimodal Intercultural Information and Communication Technology A framework for designing and evaluating multimodal intercultural communicators," in M. Kipp et al., eds., Multimodal Corpora – From Models of Natural Interaction to Systems and Applications, LNCS, Vol. 5509, pp. 160–175, Springer, 2009. ${\tt URL}\ http://dx.doi.org/10.1007/978-3-642-04793-0_10$

This talk covered the following topics:

- 1. The notion of "culture";
- 2. Challenges for the notion of culture;
- 3. Mentalism, cultural variation, cultural change;
- 4. The strength of the relation between national, region, ethnic, linguistic, political, military culture;
- 5. The notions of "intercultural communication", "crosscultural comparison";
- 6. Multicultural, intercultural, crosscultural and transcultural;
- 7. Other influences:
- 8. Cultural influence on Communication;
- 9. Understanding of cultural differences;
- 10. Methods of studying cultural differences and similarities with relevance for communication;

5.4 Models of Culture for Virtual Human Conversation

David Traum (University of Southern California – ICT, US)

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Virtual humans are artificial agents that include both a visual human-like body and intelligent cognition driving action of the body, including engaging in face to face conversation. Culture covers a wide range of common knowledge of behavior and communication that can be used in a number of ways including interpreting the meaning of action, establishing identity, expressing meaning, and inference about the performer. Virtual human behavior will always be interpreted by people from a culture-specific vantage point and viewers will make inferences about cultural aspects of the virtual humans, so whether or not an explicit model of culture is used in the design and behavior of the virtual humans, one will be attributed to them. In this talk, we will present a taxonomy of types of culture models for virtual humans and look at several examples of existing cultural models that have been used, focusing primarily on those we have developed at the Institute for Creative Technologies at University of Southern California, and point out remaining steps for a more full model of culture.

5.5 Cultural Grounding: A Dyadic Model of Culture for Agents

Justine Cassell (Carnegie Mellon University, US)

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 Joint work of Cassell, Justine; Papangelis, Alex, Zhao, Ran, Yu, Zhou, Finkelstein, Samantha, Gerritsen, Dave, Vaughn, Callie

 URL http://www.justinecassell.com/jc_research.htm

In the field of AI culture has most often been seen as a more or less explicit, internally homogeneous, externally distinctive, collective entity. However, there is data to suggest that culture is – and is better treated in AI as – identity in context – the demonstration in a particular context by a given person of a set of practices that index to members of the same group, and members of other groups, his/her cultural community membership. In this talk I propose the theory of cultural grounding to explain how humans do – and agents can – build a sense of common culture with interlocutors through the deployment of patterns of behavior and practices, with as an ultimate goal, better performance on a collaborative tasks such as peer tutoring.

5.6 Effective Cultural Models: An Industry Perspective

W. Lewis Johnson (Alelo Inc. – Los Angeles, US)

Computational models of cultural behavior are increasingly finding their way into applications, especially training applications, and are having a significant impact. From an industry perspective, questions that seem problematic for the field in general, such as how to evaluate computational models of culture, are relatively specific and straightforward. A computational model of culture is good if it is fit for purpose, i.e., it can be employed effectively to achieve the desired outcome. In the case of cross-cultural training, the goal is to enable learners to acquire the necessary skills to work successfully with people of other cultural backgrounds.

Focusing on the desired effect is critical when modelling culture, because it determines what aspects of culture to focus on. Without such a focus one can easily come up with a model that is too broad and too shallow to be useful. For example when training people to work in foreign countries it is not sufficient to use general models of the culture of the target country. One must prepare people for the cultural diversity that they will experience, as well as the particular subcultures in which they will work – e.g., business culture, military culture, etc. Thus a situation-specific, idiocultural approach is more useful than an approach that deals with national cultures in general terms.

The presentation included examples from cultural awareness training systems that incorporate agents that exhibit culturally accurate behavior in common work contexts.

6 Open Problems

Before the seminar started, a survey was conducted amongst 25 members of the research community to identify the main challenges related to the seminar's topic. In total, the

following four key areas were identified, with their associated questions being tackled by the different work groups at the seminar:

Foundations of computational models of culture

- How do different disciplines (psychological, anthropological, and sociological) approach and conceptualize culture and how does the disciplinary perspective affect computing models?
- What are the intersections between culture, personality, gender etc.?
- How to decrease the risk of cultural stereotyping during model building?
- How to handle cultural variation and change?

Paradigms for cross-cultural data collections

- Where can we find solid ground for culture-specific agent behavior?
- What kind of culture-specific behavioral data should be collected and how should the data be coded?
- How to separate individual from culture-specific variations in the collected data?
- How to handle the interdependencies between culture, emotions and personality in data collections?
- How to create a databank for observation-based studies of cultural differences?
- How to exchange corpora of culture-specific verbal and non-verbal behaviors?

Building computational models of culture

- What is the right level of abstraction for representing cultural differences in a computational model?
- How to operationalize existing cultural theories from the social sciences?
- How to model the impact of culture on emotion and decision making in social settings, such as negotiation or conflict resolution?
- How to build dyadic models of cultural interaction between humans and agents?
- How to tailor multimodal verbal and non-verbal behaviors to an agent's assumed cultural background?
- How to handle interactions between culture, affect, and cognition, and their impact on individual agent design, multi-agent interactions, and agent-human interactions?
- How to model the influence of culture on the agent's theory of mind?
- How to model culture as a plug-in on existing models?

Evaluation of computational models of culture

- How to evaluate computational models of culture and the agents based on them?
- How to evaluate the effect of the interaction between the agent's culture and the human's culture?
- What could be a proper metrics for such assessments?
- What test base is needed before a simulation can be deemed cross-culturally valid?
- How to handle the interaction of culture with other individual characteristics, such as emotion and personality in such evaluations?
- How to address the cultural bias of researchers and scholars in evaluations?

7 Working Groups

The results of the previous survey were presented to the participants at the beginning of the seminar, and the participants were invited to come up with additional ideas for break out groups. In the first round of break out groups the focus was on theories, architectures, data,

evaluation and applications. In the second round of break out groups we discussed specific applications to concretize our ideas.

7.1 Break Out Group 1 – Foundations

Participants: Gert Jan Hofstede, Catholijn Jonker, Toyoaki Nishida, Jens Allwood, Emmanuel Blanchard, Matthias Rauterberg, Colette Faucher, Catherine Pelachaud.

In the beginning, the following themes were identified by this break out group:

- Levels of abstraction and conceptualization
- Social & cultural meaning of the physical world
- Laughter & culture
- What aspects of culture are computable? And in the reverse: which parts of culture cannot or are difficult to be parameterized?

The group decided to take laughter as the leading topic. The main conclusion was that laughter turned out to have an amazing variety of social functions. At the same time biologically laughing is a pretty straightforward adaptation of a sort of startle response, if we leave out the smile that says "I'll not attack you". So that response has become mapped onto many social situations. One can laugh:

- Because something is funny (laugh your head off; this tends to be about combining domains that are normally not combined)
- To make a power move at someone (laugh at someone)
- To create good atmosphere (give status to the group that is present; have a laugh)
- To claim status (laugh about one's own joke)
- To belittle some trouble (laugh away something)

As a consequence, how one would model laughter depends on the ontology of the modelled world. Another conclusion was that all of the functions of laughter are universal, but the frequency and the kind of situations in which they occur vary from one culture to another.

In addition to the topic of laughter, the group also discussed what properties make a "good" model of culture. The following list was proposed:

- Predictability (should be mandatory)
- The ultimate goal is for a theory to be true (maybe can't be achieved but one should strive towards it) (true = that matches reality) (should be mandatory)
- Consistent (it nevers contradict itself) but the culture itself could sometimes be inconsistent
- Exhaustive (all the relevant features are considered)
- The simplest as possible given other characteristics (Occam's Razor) (useful but not mandatory)
- Perspicuous (easy to see the structure of the theory) (useful but not mandatory)
- Fruitful (useful; it has to bring new things)
- Transformation from theoretical framing (computational model?) to applications should be parameterizable (there was some disagreement)

Although this list is quite demanding, the group agreed that in order to reach a good model there could be intermediate steps.

7.2 Break Out Group 2 – How to build models of cultural agents?

Participants: Jan M. Allbeck, Nadia Berthouze, Timothy Bickmore, Justine Cassell, Dirk Heylen, Kristiina Jokinen, Sarit Kraus, Brigitte Krenn, Bilyana Martinovski, Yukiko I. Nakano, Ana Paiva (Rapporteur), Catherine Pelachaud, David R. Traum.

In this break out group, we first collected a number of research questions that should be studied when building models of cultural agents:

- How to take models of culture and turn them into computational models?
- How to build agents that assess the culture of the user?
- What architectures are currently been used and how can they be turned into culturally adaptive/adaptable ones?
- What methodologies to come up with to build these models?

To build models of cultural agents, we need to decide which kind of agent we would like to model. We identified three kinds of agent:

- Agents that are culturally sensitive (that are aware of cultures of others)
- Agents that portray a "culture"
- Agents that adapt to or co-create a culture that emerges from social interaction with users or other agents

In this break out group, we also discussed the distinction between data-driven and theorydriven methodologies for designing cultural agents. We came to the conclusion that there are no pure data driven approaches because also data driven approaches assume some kind of theory. Furthermore, we discussed to what extent agent systems could be learnt from data and/or from interaction. In this context, we also discussed dialogue phenomena, such as alignment and mirroring, and shared norms that can emerge from interaction with others.

The following features can be influenced by culture: appearance, observable behaviors (action, language and nonverbal behavior), meanings/function/conceptual structure/ontologies (power, status, theory of mind, values, and emotions), context (physical and social environment) and goals. Another view of what elements are influenced by culture is reflected by the following definition:

An agent can be defined as Agent = (I, Ei, A, u, G, M, H) where:

- \blacksquare I Internal state of the agent;
- \blacksquare A Actions;
- \blacksquare Ei Environment representation from the agent's point of view;
- \blacksquare M Agent's model of the other agents (e.g. ToM)
- \blacksquare G Goals;
- \blacksquare H History;

D is a process that takes (I, Ei, A, u, G, M, H) and generates an action.

The final conclusion of this break out group was that most of the features we build into agents should be dependent on "culture".

7.3 Break Out Group 3 – Evaluation

Participants: Elisabeth André, Ruth Aylett, Lynne Hall, Rüdiger Heimgärtner, Chad Lane (Rapporteur), Matthias Rehm.

In this work group we discussed how to use (and evaluate the use of) theories of culture. The outcome of this break out group was a list of guidelines that are presented in the diagram in Fig. 2.



Figure 2 Guidelines for using and evaluating theories of culture.

7.4 Break Out Group 4 – Applications

Participants: Hirotaka Osawa, Béatrice Hasler, Phaedra Mohammed, Rilla Khaled, Nick Degens (Rapporteur), Felix Kistler, Suleman Shahid, Kobi Gal.

The goal of this work group was to discuss how cultural models can be used in educational or persuasive applications. We argue that instead of trying to create a comprehensive cultural model, we should aim to create a simple cultural model that is sufficient to achieve the goal of the application. Such models could then be expanded upon by other researchers to create more generalizable tools.

By discussing previous research, we were able to identify three important questions that, if answered, will help to determine the requirements for the design of cultural models in the future:

1. How do we identify the cultural background of application users and manage their opinions of other cultures?

There are few reasons why it is important that the cultural background of users can be identified before interacting with the application. Firstly, the application may only be intended for a specific group of people, so it is important to ensure that there is an

objective way to classify the user's cultural background. Secondly, the cultural background may significantly influence interpretation of behavior, which may impact the use of the application.

This identification can be quite hard though, because there are no sufficiently rich classification schemes. This is due to the level of aggregation; there is a lot of data on features of national cultures, but this may not be useful if one is interested in different levels of analysis. To deal with this problem, one could generate new features of certain cultures through the use of machine learning or gathering/using data on specific groups. How people perceive other cultures is also important, for instance when your goal is to reduce prejudice. A lack of properly instantiating cultural behavior in the application may lead to the creation of new stereotypes. Even if people are not aware of the relevant culture, they will still have expectations, based on the appearance or behavioral cues of the agent, so these will need to be managed somehow.

2. How do we integrate and adapt culture in persuasive and educational applications (classifying context, social and cultural elements)?

It is important to create a strong link between cultural models and the context within an application. This link would need to take the shape of an ontology, involving a classification scheme of a certain context in terms of functional, social and cultural elements. It is important to ensure that there is a difference between the social and the cultural level, as there are universal constants, such as mimicking and synchrony, which can occur in every social context.

There are many advantages to the use of such a classification scheme. Firstly, it would help the agent to take multiple roles in an interaction, e.g. they can be part of an intercultural conflict, or act as a mediator in a conflict. Secondly, it will help autonomous agents to better understand the (social) context without need for human intervention, thus increasing the agency of the agent. Lastly, the content of the tool could be dynamically adjusted based on the cultural background of users.

3. How do we create engaging applications using cultural differences and interaction modalities?

To ensure that the interaction of users with applications is engaging, one should determine how game mechanics can be mapped to cultural models. For example, one could add leader boards for cultures that are very competitive. This would lead to a set of guidelines for creating new serious games or gamifying existing games for specific cultures.

With regards to interaction modalities, it is important to ensure that the user is able to act out culturally appropriate behaviors in an intuitive manner. As such, we need a methodology for determining intuitive gestures, and ensure that we are able to link these gestures to cultural differences, for example through the use of a gesture-intention translator.

Conclusion: It is difficult to apply cultural models to applications, so it is important to create models that are simple enough to instantiate, but complex enough to allow for social interaction. These models would need to be generalizable, to ensure that they can be used and expanded upon by other researchers.

While difficult, it is worthwhile to ensure a successful integration, as agents bring many benefits to applications, such as creating a self-contained training tool, or helping the user in an objective manner.

7.5 Break Out Group 5 – Paradigms for Data Collection

Participants: Birgit Endraß, Lewis Johnson, Tomoko Koda, Lydia Lau (Rapporteur), Samuel Mascarenhas, Kasper Rodil.

In this break out group, we concluded that there are two main paradigms for data collection of cultural phenomena: ethnographic and controlled studies. Our conclusion was that the two paradigms can complement each other and can be ideally combined to provide a greater understanding of culture. However, the existing methodologies and validation procedures for each paradigm are quite distinct, as summarized in Figure 3 and Figure 4. In the future, we propose that a bigger effort should be made in facilitating the integration of both paradigms when collecting data.

Type of data	Data development methods	Validation
Field notes	Note taking / communications are being observed within an activity	Correlation of findings from different sources (triangulation)
Observation in naturalistic setting (videos, audio)	Transcription, annotation & commentary	Ditto; subject-matter experts (emic, etic)
Interviews	Skills of the interviewers to elicit responses; sensitive to the environment /context.	Another anthropologist / experienced researcher to review interview protocol.
Questionnaires	Design of the questions, interpretation of replies	Pilot testing questionnaire
User generated digital media (for text, video, discussion forums)	Means to identify context; need to understand the activity within which the communication took place; characteristics of participants; tools to filter/focus areas for analysis	Supplement by other data collection methods to gain insight for sensible interpretation

Figure 3 Ethnographic Studies.

Type of data	Data development methods	Validation
Participants' observation in controlled setting (e.g. videos, audio recording, or other sensor data such as EEG etc.)	Transcription, annotation & commentary (ideally more than one coders, methods appropriate to the sensor data, theory such as speech act)	Inter coder agreement ; Reliability of data; Accuracy rate
Interview/ questionnaires	As in naturalistic setting	As in naturalistic setting
Log data	Coding on log data; correlate the log data with other data; usually involve automatic processing	Validity check on the log data; any other measurements appropriate for the study.

Figure 4 Controlled Studies.

7.6 Second Round Groups

To concretize our ideas, we decided to focus on specific application scenarios of cultural agents in the second round of breakout sessions. Examples included:

- A Training Agent for Oversea Students: We discussed the learning goals of a training agent for graduate students planning to study abroad.
- A Triage Agent: We developed a research and development plan for a culturally-adaptive hospital reception agent.
- An Agent to Encourage Physical Exercise: We discussed the case of a physiotherapist for chronic pain management and discussed how such an agent can be informed by theories and data.
- Teaching Conflict Resolution: We outlined the learning goals for designing an agent who can teach children conflict resolution.
- A Haggling Agent: We recorded videos of role play with seminar participants to illustrate how advice in haggling scenarios can be practiced with a haggling coach.

8 Selected Publications

8.1 Preparing Emotional Agents for Intercultural Communication

Elisabeth André (Universität Augsburg, DE)

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Main reference E. André, "Preparing emotional agents for intercultural communication," in R. Calvo, S. D'Mello, J. Gratch, A. Kappas, eds., Handbook on Affective Computing, Oxford University Press, to appear.

Although many papers emphasize the need to incorporate cultural values and norms into emotional agent architectures, work that actually follows such an integrative approach is rare. To construct anthropomorphic agents that show culture-specific emotional behaviors, researchers must investigate how emotions are conveyed across cultures and how this knowledge can be used to tune emotion recognizers to a particular culture. Models of appraisal and coping have to be enriched by models of culture to simulate how the agent appraises events and actions and manages its emotions depending on its alleged culture. Finally, mechanisms are required to modulate the expressiveness of emotions by cultural traits to convey emotions with right level of intensity and force. Starting from work done in the agent research community, we discuss how existing work on equipping anthropomorphic agents with emotional behaviors can be extended by considering culture-specific variations.

8.2 Werewolves, Cheats, and Cultural Sensitivity

Ruth Aylett (Heriot-Watt University, UK)

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 Joint work of Ayett, Ruth; Lim, Mey Yii; Ritter, Christopher; Nazir, Asad; Hall, Lynn; Tazzyman, Sarah; Paiva, Ana; Endraß, Birgit; André, Elisabeth; Hofstede, Gert Jan; Kappas, Arvid
 Main reference R. Aylett, M. Y. Lim, L. Hall, B. Endraß, S. Tazzyman, C. Ritter, A. Nazir, A. Paiva, G. J. Hofstede, E. André, A. Kappas, "Werewolves, Cheats, and Cultural Sensitivity," in Proc. of the 13th Int'l Conf. on Autonomous Agents and Multiagent Systems (AAMAS'14), pp. 1085–1092, IFAAMAS, 2014.
 URL http://aamas2014.lip6.fr/proceedings/aamas/p1085.pdf

This paper discusses the design and evaluation of the system MIXER (Moderating Interactions for Cross-Cultural Empathic Relationships), which applies a novel approach to the education of children in cultural sensitivity. MIXER incorporates intelligent affective and interactive characters, including a model of a Theory of Mind mechanism, in a simulated virtual world. We discuss the relevant pedagogical approaches, related work, the underlying mind model used for MIXER agents as well as its innovative interaction interface utilising a tablet computer and a pictorial interaction language. We then consider the evaluation of the system, whether this shows it met its pedagogical objectives, and what can be learned from our results.

8.3 The Impact of Linguistic and Cultural Congruity on Persuasion by Conversational Agents

Timothy Bickmore (Northeastern University, US)

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 Joint work of Langxuan, Yin; Bickmore, Timothy; Cortés, Dharma;
 Main reference L. Yin, T. W. Bickmore, D. E. Cortés, "The Impact of Linguistic and Cultural Congruity on Persuasion by Conversational Agents," in Proc. of the 10th Int'l Conf. on Intelligent Virtual Agents (IVA'10), LNCS, Vol. 6356, pp. 343–349, Springer, 2010.
 URL http://dx.doi.org/10.1007/978-3-642-15892-6_36

We present an empirical study on the impact of linguistic and cultural tailoring of a conversational agent on its ability to change user attitudes. We designed two bilingual (English and Spanish) conversational agents to resemble members of two distinct cultures (Anglo-American and Latino) and conducted the study with participants from the two corresponding populations. Our results show that cultural tailoring and participants' personality traits have a significant interaction effect on the agent's persuasiveness and perceived trustworthiness.

8.4 Designing Culturally-Aware Tutoring Systems with MAUOC, The More Advanced Upper Ontology Of Culture.

Emmanuel G. Blanchard (IDÛ Interactive Inc. – Montréal, CA

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© Emmanuel G. Blanchard Joint work of Blanchard, Emmanuel G: Rijchiro Mizoguchi

Main reference E. G. Blanchard, R. Mizoguchi, "Designing Culturally-Aware Tutoring Systems with MAUOC, The More Advanced Upper Ontology Of Culture," Research and Practice in Technology Enhanced

 $\label{eq:learning} Learning, 9(1):41-69, 2014. \\ \texttt{URL} \ http://www.apsce.net/uploaded/filemanager/f0135fcd-8156-48b3-82f1-b9c06b88b4d8.pdf$

TEL systems are reaching societies where they were almost completely unavailable previously. This makes the importance of culture in TEL systems more salient as they need to accommodate an expanding cultural-geographical user base. Indeed it is known that culture has a huge impact on educational expectations and norms, and the way people efficiently learn. However, culture remains a difficult concept to integrate into the already complex TEL microcosm, and the design and development of theory-grounded Culturally-Aware Tutoring Systems (CATS) thus requires guidance. The More Advanced Upper Ontology of Culture (MAUOC) is introduced in this paper as a way to address the cultural gap. It concentrates and structures in one place the many scientific-grade notions needed to get a coherent view of the cultural domain while translating them into a common ground. As such, it offers theory-grounded guidelines for culture integration in TEL.

8.5 'What I see is not what you get': Why culture-specific behaviours for virtual characters should be user-tested across cultures

Nick Degens (Wageningen University, NL)

© Nick Degens

Joint work of Degens, Nick; Hofstede, Gert Jan; Beulens, Adrie; Endraß, Birgit; André, Elisabeth

Main reference N. Degens, G. J. Hofstede, A. Beulens, B. Endraß, E. André, "'What I see is not what you get': Why culture-specific behaviours for virtual characters should be user-tested across cultures," to appear.

URL http://www.nickdegens.nl/research/publications/

Integrating culture into the behavioural models of virtual characters requires knowledge from very different disciplines such as cross-cultural psychology and computer science. If culturerelated behavioural differences are simulated with a virtual character system, users might not necessarily understand the intent of the designer. This is, in part, due to the influence of culture on not only users, but also designers. To gain a greater understanding of the instantiation of culture in the behaviour of virtual characters, and on this potential mismatch between designer and user, we have conducted two experiments. In these experiments we tried to simulate one dimension of culture (Masculinity vs. Femininity) in the behaviour of virtual characters. We created four scenarios in the first experiment, and six in the second. In each of these scenarios the same two characters interact with each other. The verbal and nonverbal behaviour of these characters differ depending on their cultural scripts. In two user perception studies, we investigated how these differences are judged by human participants with different cultural backgrounds. Besides expected differences in perception between participants from Individualistic and Collectivistic countries. We also found that the user's interpretation of the character's motivation had a significant influence on the perception of the scenarios. Based on our findings, we give recommendations for researchers that aim to design culture-specific behaviours for virtual characters.

8.6 Cultural Diversity for Virtual Characters

Birgit Endraß (Universität Augsburg, DE)

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 Main reference B. Endraß, "Cultural Diversity for Virtual Characters – Investigating Behavioral Aspects across Cultures," ISBN 978-3-658-04909-6, Springer, 2014.
 URL http://dx.doi.org/10.1007/978-3-658-04910-2

In human conversation, meaning is transported through several channels such as verbal and nonverbal behavior. Certain of these behavioral aspects are culturally dependent. Mutual understanding or acceptance is thus, amongst others, dependent on the cultural background of the interlocutors. When designing virtual character behavior, culture should be considered as it may improve the character's acceptance by users of certain cultural backgrounds.

In this dissertation, the simulation of culture with virtual characters is investigated. Thereby the focus lies on the generation of different culture-related behaviors by integrating culture as a parameter into the behavioral models of virtual characters, rather than simulating obvious differences such as outer appearance or language.

In the scope of this dissertation, aspects of verbal behavior, communication management and nonverbal behavior were explored and exemplified for the German and Japanese cultures. These aspects are of special interest, since they are dependent on culture, and address different modalities of a virtual character's behavior. For the integration of culture into computational models, a hybrid approach was developed that combines the advantages of a model-based approach and a corpus-driven approach. The hybrid approach enables us to model the causality of culture and corresponding behavior in a generalizable manner while concrete behaviors can be extracted from empirical data.

For the generation of culture-specific behaviors, methodologies from Artificial Intelligence were applied, in particular distributed behavior planning and Bayesian networks, and simulated in a 3D virtual environment. To evaluate the culture-related behaviors, perception studies were conducted in both targeted cultures. Results indicate that human observers tend to prefer character behavior that was designed to resemble their own cultural background. For the behavioral aspects where our hypotheses were confirmed, we consider their attention when designing virtual character behavior as promising. We aim on contributing to the field of intelligent virtual agents by providing our findings that can help improve a character's acceptance by users of certain cultural backgrounds.

However, the integration of cultural background into the behavioral models of virtual characters can not only enhance their acceptance, but also be used for cultural training in virtual environments, for the localization of computer games, or for cultural heritage by preserving and transferring culture-specific behaviors. Although the workflow has been applied to two national cultures, it is of a general nature and can serve as a guidance for other culture-specific generation approaches.

8.7 Modeling Psychological Theories of Emotion and Social Identity for Helping the Conception of Psychological Messages: the System **PSYMDEV**

Colette Faucher (Aix-Marseille University, FR)

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Creative Commons BY 3.0 Unported license Colette Faucher Joint work of Faucher, Colette; Machtoune, Malika Main reference C. Faucher, M. Machtoune, "Modeling Psychological Theories of Emotion and Social Identity for Helping the Conception of Psychological Messages: the System PSYMDEV," Poster Presentation, in Preliminary Proc. of the 23rd Conf. on Behavior Representation in Modeling and Simulation (BRIMS'14), 2 pp., 2014. URL http://cc.ist.psu.edu/BRIMS/archives/2014/Faucher_BRIMS2014.pdf

In asymmetric conflicts, the Armed Forces generally have to intervene in countries where the internal peace is in danger. They must make the local population an ally in order for them to be able to deploy the necessary military actions with its support. For this purpose, psychological operations (PSYOPS) are used to shape people's behaviors and feelings by spreading out messages thanks to different media (tracts, loudspeakers, video clips, etc.). In this paper, we present PSYMDEV (PSYchological Message DEViser), a system that helps the military analyst to construct messages that trigger specific emotions in members of the population selected by social criteria like age or political opinion and called the info-targets. Given such a sociocultural group and a feeling that the latter must feel, the system provides a twofold-situation that consists of, on the one hand, a categorization-situation meant to induce a positive or negative initial state of mind in the info-targets depending on the type of emotion to be triggered through a psychological mechanism inspired by theories stemming from Social Psychology and an action-situation aiming at effectively triggering the specific feeling through a psychological process explained by the Intergroup Emotion Theory, an extension of the Appraisal Theory of Emotions. These situations are illustrated by means of images or a film or some auditive elements, thanks to adapted media generally used by the military like tracts or video clips, for example. Therefore, the twofold-situation gives birth to a psychological message intended to trigger an emotion.

8.8 The Effects of Culturally Congruent Educational Technologies on **Student Achievement**

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Joint work of Finkelstein, Samantha; Yarzebinski, Evelyn; Vaughn, Callie; Ogan, Amy; Cassell, Justine

Main reference S. Finkelstein, E. Yarzebinski, C. Vaughn, A. Ogan, J. Cassell, "The Effects of Culturally Congruent Educational Technologies on Student Achievement," in Proc. of the 16th Int'l Conf. on

Artificial Intelligence in Education (AIED'13), LNCS, Vol. 7926, pp. 493–502, Springer, 2013. URL http://dx.doi.org/10.1007/978-3-642-39112-5_50

Dialectal differences are one explanation for the systematically reduced test scores of children of color compared to their Euro-American peers. In this work, we explore the relationship between academic performance and dialect differences exhibited in a learning environment by assessing 3rd grade students' science performance after interacting with a "distant peer" technology that employed one of three dialect use patterns. We found that our participants, all native speakers of African American Vernacular English (AAVE), demonstrated the strongest science performance when the technology used AAVE features consistently throughout the

interaction. These results call for a re-examination of the cultural assumptions underlying the design of educational technologies, with a specific emphasis on the way in which we present information to culturally-underrepresented groups.

8.9 Reflections on a Model of Culturally Influenced Human-Computer Interaction to Cover Cultural Contexts in HCI Design

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 Rüdiger Heimgärtner

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 R. Heimgärtner, "Reflections on a Model of Culturally Influenced Human–Computer Interaction to Cover Cultural Contexts in HCI Design," International Journal of Human-Computer Interaction, Special Issue on Reframing HCI Through Local and Indigenous Perspectives, 29(4):205–219, 2013.

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This article presents an approach covering cultural contexts in human-computer interaction (HCI) design using a model of culturally influenced HCI. Cultural influence on HCI is described using cultural variables for user interface design. Assumptions regarding the influence of culture on HCI, considering the path of the information processing and the interaction style between Chinese and German users are explained on the basis of cultural models. Subsequent indicators represent the relationship between culture and HCI (culturally imprinted by the user). Correlations adopted theoretically between cultural dimensions and variables for HCI design are investigated. These correlations represent first relevant constituents of a model for culturally influenced HCI. Considerations applying such a model and evidence for the proper application of the method are presented. The proposed analysis of the context of users in general is presented, and some challenges evolving from the intercultural HCI design process from local and indigenous perspectives are addressed. The descriptive intercultural model for HCI design serves to inspire HCI engineers in the requirement analysis phase as well as HCI designers in the design phase. Finally, some implications for practitioners are shown, including HCI style scores, to prognosticate the effort and the expenditure for taking into account the cultural context in intercultural user interface design.

8.10 Intercultural User Interface Design

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Main reference R. Heimgärtner, "Intercultural User Interface Design," in K. Blashki and P. Isaias, eds., Emerging Research and Trends in Interactivity and the Human-Computer Interface, pp. 1–33, IGI Global, 2014.

 ${\tt URL} \ http://dx.doi.org/10.4018/978-1-4666-4623-0.ch001$

This chapter starts with an introduction illuminating the theoretical background necessary for taking culture into account in Human Computer Interaction (HCI) design. Definitions of concepts used are provided followed by a historical overview on taking culture into account in HCI design. Subsequently, a glimpse of the current state of research in culture-centered HCI design is derived from secondary literature providing the gist of the structures, processes, methods, models, and theoretic approaches concerning the relationship between culture and HCI design. Controversies and challenges are also mentioned. A short discussion of results from empirical studies and design recommendations for culture-centered HCI design lead to implications and trends in future intercultural user interface design research.

8.11 Cultural Differences in Human-Computer Interaction – Towards Culturally Adaptive Human-Machine Interaction

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 Main reference R. Heimgärtner, "Cultural Differences in Human-Computer Interaction. Towards Culturally Adaptive Human-Machine Interaction," ISBN 978-3-486-71989-5, De Gruyter, 2012.
 URL http://www.degruyter.com/view/product/232226

The work makes a contribution to the investigation of cultural factors in Human-Machine Interaction (HMI). Cultural influences can be described by intercultural variables which are imprinted differently depending on the respective specific culture and provide concrete design tasks for the design of HMI. Different cultural models are presented. Assumptions are derived from them regarding the influence of culture on HMI. These assumptions encompass differences about information processing and interaction style between Chinese and German users.

Cultural differences in Human-Computer Interaction (HCI) and culturally adaptive systems are not separable from each other because of safety issues. On the one hand, the regulation of cultural differences in HCI represents the first step towards developing culturally adaptive systems. On the other hand, the results of the cultural differences only become applicable in HCI by culturally adaptive systems in areas relevant to safety. E.g. a cultural customization is only automatically possible for driver navigation systems during the journey. Technical products like the driver navigations systems treated as examples in this dissertation are becoming more complex in functionality and interaction possibilities. Additionally, due to the expansion of global markets, products and systems need development for possible worldwide usage. One possible method of coping with intercultural complexity is to apply adaptive systems.

The concept of cross-cultural adaptive HMI is discussed and the influence of culture on driver navigation systems and cases of cross-cultural adaptability in driver navigation systems are presented. Thereby, the reasons, advantages and problems of using adaptability will be addressed. An important prerequisite for cultural adaptability is to classify the user quantitatively by the system according to culturally influenced interaction patterns. This work concentrates on describing a method to obtain quantitatively discriminating cultural interaction indicators and their values for cross-cultural Human-Computer Interaction design as preparatory work for culturally adaptive navigation and multi-media systems.

The method has been implemented in a tool for intercultural HCI analysis. Two empirical studies have been carried out providing HCI analysis during several test sessions. Test persons of different cultures did several tasks using this test tool. A first offline pre-study indicated interesting results and provided new insights that have subsequently been verified by two online studies. These studies revealed differences in human-computer interaction that depend on the cultural background of the users (e.g., attitude, preference, skill, etc.) and proved that the test tool was working properly. Furthermore, doing those empirical studies, the cultural differences in HCI have been found quantitatively, which fulfills a prerequisite for automatic cultural adaptability. Cultural dimensions are related to culturally different conceptions held by human beings about space, time and communication, which have implications for their expectations (e.g., number and order of information units).

Several cultural interaction indicators exhibiting informational characteristics are presented which taken together describe an interaction pattern of the user with the system. Additional qualitative studies confirmed the necessity of the quantitative studies as well as

Elisabeth André, Ruth Aylett, Gert Jan Hofstede, and Ana Paiva

confirming the truth of the results in this study. The results are presented and discussed to demonstrate the difficulties, but also the importance of understanding cultural differences in HCI to clear the way for cultural adaptability. Moreover, theoretically postulated correlations between cultural dimensions and variables for HMI design have been analyzed using statistical methods. Based on the results, a model with cultural variables for intercultural HMI design has been developed from which a usability metric trace model containing quantitative cultural interaction indicators was derived and empirically verified. This model served to adapt rules that have been implemented in a demonstrator to prove that cultural adaptability works in reality and not only statistically.

The basic postulated principle of culturally adaptive human-machine interaction (CAHMI) can be improved upon empirically as found in the results of this work. The user interface can be adapted automatically according to the culturally influenced interaction patterns of the user. From this, also with regard to driver navigation systems, several recommendations for the design of 'intercultural user interfaces' are derived and culturally adaptive interface agent architecture as well as a generic adaptability framework is suggested.

8.12 Robotic Rabbit Companions: amusing or a nuisance?

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 Main reference D. Heylen, B. van Dijk, A. Nijholt, "Robotic Rabbit Companions: amusing or a nuisance?," Journal on Multimodal User Interfaces, 5(1-2):53-59, 2012; available also at EEMCS.
 URL http://dx.doi.org/10.1007/s12193-011-0083-3
 URL http://eprints.eemcs.utwente.nl/21166/

Most of the studies in human-robot interaction involve controlled experiments in a laboratory and only a limited number of studies have put robotic companions into people's home. Introducing robots into a real-life environment does not only pose many technical challenges but also raises several methodological issues. And even though there might be a gain in ecological validity of the findings, there are other drawbacks that limit the validity of the results. In this paper we reflect on some of these issues based on the experience we gained in the SERA project where a robotic companion was put in the homes of a few people for ten days. We try to draw some general lessons from this experience.

8.13 Modelling Trade and Trust Across Cultures

Catholijn Jonker (Delft University of Technology, NL)

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Main reference G. J. Hofstede, C. M. Jonker, S. Meijer, T. Verwaart, "Modelling Trade and Trust Across Cultures," in Proc. of the 4th Int'l Conf. on Trust Management (iTrust'06), LNCS, Vol. 3986, pp. 120–134, Springer, 2006.

URL http://dx.doi.org/10.1007/11755593_10

Misunderstandings arise in international trade due to difference in cultural background of trade partners. Trust and the role it plays in trade are influenced by culture. Considering that trade always involves working on the relationship with the trade partner, understanding

the behaviour of the other is of the essence. This paper proposes to involve cultural dimensions in the modelling of trust in trade situations. A case study is presented to show a conceptualisation of trust with respect to the cultural dimension of performance orientation versus cooperation orientation.

8.14 Game Design Strategies for Collectivist Persuasion

Rilla Khaled (University of Malta, MT)

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 Main reference R. Khaled, P. Barr, R. Biddle, R. Fischer, J. Noble, "Game design strategies for collectivist persuasion," in Proc. of the 2009 ACM SIGGRAPH Symp. on Video Games (Sandbox'09), pp. 31–38, ACM.
 URL http://dx.doi.org/10.1145/1581073.1581078

A fundamental feature of serious games is persuasion, an attempt to influence behaviors, feelings, or thoughts. Much of the existing research on serious games and, more generally, on persuasive technology (PT), does not address the important links between persuasion and culture. It has tended to originate from Western, individualist cultures, and has focused on how to design for these audiences. In this paper, we describe the design of one of two versions of a serious game we developed about quitting smoking titled Smoke? which is targeted at collectivist players. We show how the design was informed by persuasive strategies we identified from the crosscultural psychology literature, intended for use in games for players of collectivist cultures: HARMONY, GROUP OPINION, MONITORING, DISESTABLISHING, and TEAM PERFORMANCE. We then discuss the results of a quantitative investigation of the effects of both game versions on both individualist and collectivist players.

8.15 Traveller: An Interactive Cultural Training System controlled by User-Defined Body Gestures

Felix Kistler (Universität Augsburg, DE)

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Joint work of Kistler, Felix; André, Elisabeth; Mascarenhas, Samuel; Silva, André; Paiva, Ana; Degens, Nick; Hofstede, Gert Jan; Krumhuber, Eva; Kappas, Arvid; Aylett, Ruth

Main reference F. Kistler, E. André, S. Mascarenhas, A. Silva, A. Paiva, N. Degens, G. J. Hofstede, E. Krumhuber, A. Kappas, R. Aylett, "Traveller: An interactive cultural training system controlled by user-defined body gestures," in Proc. of the 14th IFIP TC 13 Int'l Conf. on Human-Computer Interaction (INTERACT'13), LNCS, Vol. 8120, pp. 697–704, Springer, 2013.

In this paper, we describe a cultural training system based on an interactive storytelling approach and a culturally-adaptive agent architecture, for which a user-defined gesture set was created. 251 full body gestures by 22 users were analyzed to find intuitive gestures for the in-game actions in our system. After the analysis we integrated the gestures in our application using our framework for full body gesture recognition. We further integrated a second interaction type which applies a graphical interface controlled with freehand swiping gestures.

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8.16 Pros and Cons of Displaying Self-Adaptors: Importance of Considering Users' Social Skills

Tomoko Koda (Osaka Institue of Technology, JP)

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 Main reference T. Koda, H. Higashino, "Pros and Cons of Displaying Self-Adaptors: Importance of Considering Users' Social Skills," Workshop on Cultural Characters in games and learning (CCGL'13), 2013.
 Joint work of Hiroshi Higashino
 URL http://www.is.oit.ac.jp/~koda/hiserver01/profile-e.html

Self-adaptors are bodily behaviors that often involve self-touch. Our continuous evaluation of the interaction between an agent that exhibits self- adaptors and without indicated that there is a dichotomy on the impression on the agent between users with high social skills and those with low skills. People with high social skills feel more friendliness toward an agent that exhibits self-adaptors than those with low social skills. The result suggests the need to tailor non-verbal behavior of virtual agents according to user's social skills.

8.17 Socio-emotional effects of synthetic language varieties

Brigitte Krenn (OFAI – Wien, AT)

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Research on intelligent agents has demonstrated that the degree an artificial entity resembles a human correlates with the likelihood that the entity will evoke social and psychological processes in humans. On the other hand, language attitude studies based on natural voices have provided evidence that human listeners socially assess and evaluate their communication partners according to the language variety used. Taking the two findings together, we hypothesize that synthetically generated language varieties have social effects similar to those reported from language attitude studies on natural speech.

As a starting point for assessing the socio-emotional effects of synthetic language varieties in ECAs, the design and realization of a set of synthetic voices was presented representing standard and dialectal varieties of Austrian German. The respective voices can be accessed online via http://vsds.ofai.at/vsds_synthesize.cgi. See also [4]. Moreover, an approach to employing techniques from statistical machine translation was introduced, in order to transform textual input representing the standard variety into representations suitable as input to a dialectal text-to-speech system. See http://varieties.ofai.at/test_translate.shtml for an online demonstration of such a translation system and http://varieties.ofai.at/publications. shtml for related references.

[3] and [2] to appear provide evidence that socio-emotional effects of natural language varieties transfer to synthetic varieties. In addition, it could be shown that not only the particular variety has effects on the socio-emotional evaluation and appreciation of the respective speaker, but also features relating to the voice quality of the synthesized speech bring about attributions of different social aspects and stereotypes.

[1] investigate the effects of a virtual character's bodily expressivity and the language variety it speaks on its perceived personality. Clear evidence was found that synthesized language variety, and gestural expressivity influence the human perception of an agent's

extroversion. Whereby Viennese and Austrian standard language are perceived as more extrovert than the German standard.

Summing up, language variety, voice quality and gestural expressivity together strongly influence the attitudes of listeners towards artificial speakers, thus highlighting the importance of an accurate design of voice, language variety and body behaviour for the development of artificial agents. Moreover, agent designers may directly profit from existing results of language attitude studies on natural speech, which is an important factor, given the growing availability of synthetic voices representing different language varieties.

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8.18 Promoting Metacognition in Immersive Cultural Learning Environments

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 URL http://dx.doi.org/10.1007/978-3-642-02583-9_15

Metacognition, defined as active control over cognitive processes during learning, is a critical component in the development of intercultural competence. Progression through stages of intercultural development requires self-assessment, self-monitoring, predictive, planning, and reflection skills. Modern virtual learning environments now provide a level of immersion that enable meaningful practice of cultural skills, both in terms of visual and experiential fidelity. This paper discusses their potential role in intercultural training, and the use of intelligent tutoring and experience manipulation techniques to support metacognitive and intercultural development. Techniques for adapting the behaviors of virtual humans to promote cultural learning are discussed along with the role of explicit feedback. The paper concludes with several suggestions for future research, including the use of existing intercultural development metrics for evaluating learning in immersive environments and on the balance between implicit and explicit feedback to establish optimal conditions for acquiring intercultural competence.

8.19 Reciprocal adaptation in intercultural interaction contexts

Bilyana Martinovski (University of Stockholm, SE)

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Adaptation is a major process in evolution and it has been studied mainly in biology and zoology. In [1], Gumperz introduced the term reciprocal adaptation into the field of sociolinguistics of interpersonal communication as a procedure used by anthropology scholars in gathering data from unwritten languages. As "each participant gradually learns to adapt and to enter into the other's frame of reference... what others had seen as primitivity or failure to conform to pre-existing standards of rationality or efficiency now became evidence for the existence and functioning of cultural differences" [1]. Reciprocal adaptation and accommodation are studied as interhuman spoken language interaction phenomena [2], [3], [4]. However, the majority of previous intercultural communication studies are actually cross-cultural communication studies i.e., they do not study how people from different cultures communicate with each other but rather compare how people from different cultures reason within their own cultures and on the basis of this comparison draw expectations and assumptions on how they would communicate when they meet (e.g. [5], [6]). These expectations and assumptions are then used in intercultural communication training and education. Such approaches have come a long way but there are still issues left unexplained. Part of the reason for this is that they have taken language, communicative processes and contextual factors insufficiently into account. In effect, there is a need of consideration of communicative changes in intercultural interlingual interactions.

Reciprocal adaptation is a mechanism which changes patterns of communication in the process of communication on cognitive and linguistic levels but also on emotional and behaviour levels. Speakers adapt to each other with respect to posture, gaze, proximity, orientation, lexical choices, tone of voice, emotion expression, etc. But how do intra-cultural communication patterns change when people meet in intercultural contexts as they adapt to each other's culture-based communicative patterns? [7] found that international student groups who are trained in intercultural communication based on results from cross-cultural studies perform worse with regard to creativity in comparison to a group of international student who are not intercultural communication trained. In addition, linguistic adaptation of human agents to Virtual Humans is found also in spoken human-computer dialogues [8], which indicates that successful human-computer interaction benefits from a design based on reciprocity i.e. design of dialogue systems, which learn during and through interaction based on the principles of imitation and adaptation. Preliminary studies suggest that expectations of adaptation during face-to-face intercultural communication are sustained but the degree of the effect is not yet clear. For instance, interactive studies on intercultural communication which involve Chinese speakers have focused on differences in communication [9] rather than on the actual process and communicative relatedness between speakers However, [10] found that when Spanish and Chinese meet for a job interview role-play, Spanish use among other features, less gestures and shorter mutual gaze whereas Chinese use more gestures and longer mutual gaze than in identical intra-cultural contexts. Qui and Wang [11] also notice reciprocal adaptation during Swedish-Chinese business negotiation role-play in English. These results indicate that we need to rethink major assumptions and methods of intercultural communication study and co-design of interactive e-learning technology.

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8.20 Personality differences in the multimodal perception and expression of cultural attitudes and emotions

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 Joint work of Clavel, C.; Rilliard, A.; Shochi, T.; Martin, J. C.
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 URL http://dx.doi.org/10.1109/ACII.2009.5349504

Individual differences have been reported in the literature on nonverbal communication. Recent development in the collection and evaluation of audiovisual databases of social behaviors brings new insight on these matters by exploring other types of social behaviors and other approaches to individual differences. This presentation summarizes two experimental studies about personality differences in the audiovisual perception and expression of social affects. We conclude on the potential of such audiovisual database and experimental approaches for the design of personalized affective computing systems.

8.21 Social Importance Dynamics: A Model for Culturally-Adaptive Agents

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 URL http://dx.doi.org/10.1007/978-3-642-40415-3_29

The unwritten rules of human cultures greatly affect social behaviour and as such should be considered in the development of socially intelligent agents. So far, there has been a large focus on modeling cultural aspects related to non-verbal behaviour such as gaze or body posture. However, culture also dictates how we perceive and treat others from a relational perspective. Namely, what do we expect from others in different social situations and how much are we willing to do for others as well. In this article we present a culturally configurable model of such social dynamics. The aim is to facilitate the creation of agents with distinct cultural behaviour, which emerges from different parametrisations of the proposed model. The practical application of the model was tested in the development of an agent-based application for intercultural training, in which the model is responsible for driving the socio-cultural behaviour of the virtual agents.

8.22 Dynamic Cultural Contextualisation of Educational Content in Intelligent Learning Environments using ICON

Phaedra Mohammed (The University of the West Indies – St. Augustine, TT)

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 Main reference International Journal of Artificial Intelligence in Education, Special Issue on Culturally-Aware Educational Systems; forthcoming 2014.

Research into culturally-aware Intelligent Learning Environments (ILEs) has been motivated by interest in improving the achievements, participation and motivation of underrepresented student groups, increasing the acceptance and use of ILEs through cultural-awareness, and reducing student misinterpretations of ILEs driven by lack of culturally-aware designs. Cultural awareness, when applied to ILEs, contours the overall appearance, behaviour, and content used in these systems through the use of culturally-relevant student data and information. However in most cases, these adaptations are system-initiated with little to no consideration given to student-initiated control over the extent of cultural-awareness being used in the learning experience. In addition, many ILEs use cultural granularity at a national or country level which may over generalise the cultural backgrounds of students and fail to capture differences between subcultures in a society that are relevant to the student. As such, this talk examines some of the issues relevant to these challenges through the development of the ICON (Instructional Cultural contextualisation) system. The talk discusses the computational approaches used in ICON for modelling the diversity of students across cultures, the necessary semantic representation formalisms for culture, and the production of run-time, dynamic ILE adaptations that reflect and respond to these subtle but important differences within cultures.

8.23 Towards Computational Model of Cultural Awareness in Communication

Toyoaki Nishida (Kyoto University, JP)

Classical approaches to culture have been analytic in the sense that they rely on observations, conceptualizations, investigations, arguments, criticisms, and so on. In contrast, modern computational approaches draw on synthetic methodologies that use cultural models to simulate cultural phenomena to see their consequences under various conditions. The unique feature of the intelligent virtual agent technology is that it allows ordinary people to experience, by participation, with cultural encounters in artificial situations designed for specific purposes such as learning. These synthetic approaches bring about excellent new opportunities, as the users can gain as much direct experiences as she or he like under varieties of specified settings by changing parameter values or even by replacing models. For example, our research group leverages this characteristic to permit the user to experience with culture-depending queuing behaviors and real-time collaborations [5, 3].

A synthetic approach to culture employs a method for building conversational agents that can actively and proficiently participate in natural conversations among people. A data-intensive approach to conversational systems [4] exploits abundant data obtained from measuring conversation to enrich both interactional and transactional aspects of conversational agents. A computational model of cultural awareness and evolution in communication is a central issue for building conversational agents aware of cultural aspects in communication that can not only adapt to the cultural background of partners but also take an active role in building, extending and diffusing new cultural traits.

Provided that culture is a collective mental programming of the mind following [2], cultural difference is everywhere depending on the degree of the individual differences of mental software that may arise not only by national culture but also by educational background, business practice, or even by age. We would like our conversational agent not only to sense and adapt cultural differences but also to make an active participation such as inventing, revising and disseminating a new communication practice.

A computational theory of culture might involve such issues as:

- 1. Theory of communication. I suspect that a joint activity theory [1] might serve as a good start point. We need to build on it a computational theory of how cultural aspects manifest in a communication ladder.
- 2. Theory of cultural signals. The space of cultural signals may be captured by a parametric model, such as the one proposed in [2]. In addition, semiotics is needed to specify how signals are associated with intended meaning.
- 3. Theory of cultural cognition. It should entail how cultural signals are explicitly or implicitly encoded in communication and how people may realize and adopt them. I suspect that cultural signals are implemented as a redundancy in behaviors so participants can easily notice them; should they understand the meaning and like them, they start to spend a certain amount of cost to employ them. People may know the meaning by being told or guess it by themselves, each may correspond to the theory theory and the simulation theory in theory of mind, respectively.
- 4. Theory of cultural creation and diffusion. Creation might sometimes carefully designed, but sometimes caused by contingent events.

5. Computational theory of empathic agents. In order for a conversational agent to actively participate in cultural evolution, it need to be empathic, not only be able to sense cultural signals but also appraise them to feel other participants' emotions as well as express its own empathy to allow the partners to feel the agent's emotion.

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8.24 Emotional Cyborg: Complementing Emotional Labor using Human-agent Interaction

Hirotaka Osawa (University of Tsukuba, JP)

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Main reference H. Osawa, "Emotional Cyborg: Human Extension with Agency for Emotional Labor," in Proc. of the 2014 ACM/IEEE Int'l Conf. on Human-robot Interaction (HRI'14), p. 108, 2014. URL http://dx.doi.org/10.1145/2559636.2559647

KL http://dx.doi.org/10.1145/2559050.255904

The author proposes the notion of an emotional cyborg as a new application proposal in the human-agent interaction (HAI) field. The author summarized what kind of human processes maintain emotional labor and how such kind of social labor is supported by HAI technologies. The author implemented AgencyGlass, a prototype application, as a tool for realizing an emotional cyborg. The device is attached on a user's face and displays the user's eye gestures. The author implemented a prototype application for supplementing emotional labor with AgencyGlass and presented this as a video.

8.25 Computational modelling of culture and affect

Ana Paiva (IST – University of Lisbon, PT)

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        Second Ana Paiva

    Joint work of Aylett, Ruth; Paiva, Ana

    Main reference R. Aylett, A. Paiva, "Computational Modelling of Culture and Affect," Emotion Review,
        4(3):253-263, 2012.

    URL http://dx.doi.org/10.1177/1754073912439766
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This article discusses work on implementing emotional and cultural models into synthetic graphical characters. An architecture, FAtiMA, implemented first in the antibullying application FearNot! and then extended as FAtiMA-PSI in the cultural-sensitivity application

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ORIENT, is discussed. We discuss the modelling relationships between culture, social interaction, and cognitive appraisal. Integrating a lower level homeostatically based model is also considered as a means of handling some of the limitations of a purely symbolic approach. Evaluation to date is summarised and future directions discussed.

8.26 Child-robot interaction across Cultures

Suleman Shahid (Tilburg University, NL)

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This study investigates how children from two different cultural backgrounds (Pakistani, Dutch) and two different age groups (8 and 12 year olds) experience interacting with a social robot (iCat) during collaborative game play. We propose a new method to evaluate children's interaction with such a robot, by asking whether playing a game with a state-of-the-art social robot like the iCat is more similar to playing this game alone or with a friend. A combination of self-report scores, perception test results and behavioral analyses indicate that Child-Robot Interaction in game playing situations is highly appreciated by children, although more by Pakistani and younger children than by Dutch and older children. Results also suggest that children enjoyed playing with the robot more than playing alone, but enjoyed playing with a friend even more. In a similar vein, we found that children were more expressive in their non-verbal behavior when playing with the robot than when they were playing alone, but less expressive than when playing with a friend. Our results not only stress the importance of using new benchmarks for evaluating Child-Robot Interaction but also highlight the significance of cultural differences for the design of social robots.



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Report from Dagstuhl Seminar 14132

Interaction and Collective Movement Processing

Edited by

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Abstract

This report documents the program and the outcomes of Dagstuhl Seminar 14132 "Interaction and Collective Movement Processing". This seminar brought together a group of 30 scientists with varied backgrounds, but with a shared interest in computations involved in the processing of moving entity data, like humans or animals. The seminar focused on characterizing and modelling interaction between moving entities, and featured four invited talks in four main research fields: ecology, computational geometry, GIScience, and collective motion. The remainder of the program consisted of short presentations, open problem sessions, break-out groups to work on open problems, and reporting sessions based on research done in the break-out groups.

Seminar March 23–28, 2014 – http://www.dagstuhl.de/14132

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1 **Executive Summary**

Maike Buchin Luca Giuqqioli Marc van Kreveld Guy Theraulaz

> License (Creative Commons BY 3.0 Unported license Maike Buchin, Luca Giuggioli, Marc van Kreveld, and Guy Theraulaz

The Dagstuhl Seminar on Interaction and Collective Movement Processing brought together a group of 30 scientists with varied backgrounds, but with a shared interest in computations involved in the processing of moving entity data, like humans or animals. There are different reasons for such computations: they are needed for the initial processing (cleaning, recognition), for the analysis (derived properties, patterns), and for more advanced features like characterizing and modelling interaction between entities. This seminar focused on the latter, the hardest of these tasks. The majority of the participants had a background in ecology, behavioral sciences, or geometric algorithms, but there were also participants from statistical physics, GIScience, and computer vision.



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Interaction and Collective Movement Processing, Dagstuhl Reports, Vol. 4, Issue 3, pp. 138-152 Editors: Maike Buchin, Luca Giuggioli, Marc van Kreveld, and Guy Theraulaz DAGSTUHL Dagstuhl Reports

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Maike Buchin, Luca Giuggioli, Marc van Kreveld, and Guy Theraulaz

The seminar featured four invited talks in four main research fields: ecology (Greg Stephens), computational geometry (Jack Snoeyink), GIScience (Patrick Laube), and collective motion (Andrea Perna). The remainder of the program consisted of short presentations, open problem sessions, break-out groups to work on open problems, and reporting sessions based on research done in the break-out groups.

While the original intention was to tackle the challenging problems of interaction and collective motion, part of the research was done on other closely related topics in movement analysis, like quality issues in movement analysis. The problems that were investigated—also described in this report—have led to the start of new research, which was exactly the purpose of the seminar.

The participants enjoyed both the seminar setting and the interdisciplinarity of the seminar, which gave a new impulse to the research of many. A number of collaborations have started up, and we hope that these not only lead to publications but also to longer lasting collaborations. While all participants would be happy to return to such a seminar later, it was agreed that the focus will shift to keep the dynamics and cross-fertilization of different research fields.

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3 Invited Talks

3.1 Sampling the movement phenospace: from posture to behavior in the free-wiggling of C. elegans

Greg Stephens (VU University – Amsterdam, NL)

We apply a low-dimensional yet complete representation of body shape (eigenworms) to construct a principled parameterization of the 2D movement behavior of the nematode C. elegans. Despite it's simplicity, we show that a linear dynamical model of the eigenworm projections captures long-range temporal correlations and reveals two periodic dynamics, the primary body wave and and an oscillation between the head and body curvature which underlies arcs in the centroid trajectory. We parameterize the movement phenospace by constructing dynamical systems locally in time and show that variation within this space is remarkably restrained; with increasing window size, a single behavioral mode dominates the variance and represents the coupled control of speed and turning. The distribution of this primary mode is bimodal, suggesting a correspondence to roaming and dwelling states. Finally, we apply our behavioral parameterization to show that the worm's response to a strong impulsive heat shock includes a Hopf-like bifurcation corresponding to an early-time growth of the amplitude of the crawling wave.

3.2 Models for moving data in Computational Geometry

Jack Snoeyink (University of North Carolina – Chapel Hill, US)

The wide variety of sensors for and applications of data on motion creates a large problem space; the theory of computer science tries to classify problems to understand how solutions can generalize. In particular, computational geometry is a branch of the theory of computer science that studies the design and analysis of algorithms and data structures for problems best stated in geometric form. Because of these origins, it assumes that inputs are moving geometric objects (often points) in low dimensions, and that the desired output is a dynamic geometric graph or structure, such as the convex hull or nearest-neighbor graph, on these objects. Blunck et al. [2] observed that many types of input can be unified by assuming each object provides trajectory, which is a continuous function of its position over time—algorithms can be built on primitives that query objects at specific times or calculating the next time a pair of objects change their interaction. This decouples computation of output structure from interpolation to obtain a trajectory from sensor measurements of an object. (For the implementer: since the interpolation often even depends on object state, the interaction primitives must handle double-dispatch.) Since the algorithms on moving data need not stop, the usual efficiency measure, asymptotic worst-case running time, does not apply. Basch et al. [1] originated the analysis of kinetic data structures, which compares the worst-case number of internal changes to data structures to the worst-case number of external output changes; this analysis framework has inspired many novel data structures.
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3.3 Computational Movement Analysis

Patrick Laube (ZHAW – Wädenswil, CH)

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In the last decade, advances in tracking technologies resulted in geographic information representing the movement of individuals at previously unseen spatial and temporal granularities. This new, inherently spatiotemporal, kind of geographic information offers new insights into dynamic geographic processes but also challenges the traditionally rather static spatial analysis toolbox. This talk first makes the case for Computational Movement Analysis (CMA), as an interdisciplinary umbrella for contributions from a wide range of fields aiming for a better understanding of movement processes, including GIS, spatiotemporal databases and data mining. Then the talk will discuss three aspects of CMA: (1) Characteristics of spatio-temporal movement data, especially implicit relationships, uncertainty, and scale, (2) conceptual modeling of movement and movement spaces, (3) a range of analysis methods that GISciences contributes to movement analysis, including (i) bridging the semantic gap, (ii) privacy issues related to movement data involving people, (iii) the arrival of big and open data in movement analysis, and (iv) opportunities for decentralized CMA arising from the internet of things.

3.4 Collective Motion

Andrea Perna (Paris Interdisciplinary Energy Research Institute, FR)

Collective animal behaviour is the study of how interactions between individuals produce group level patterns, and why these interactions have evolved. This study has proved itself uniquely interdisciplinary, involving physicists, mathematicians, computer scientists, engineers and biologists. Almost all experimental work in this area is related directly or indirectly to mathematical models, with regular movement back and forth between models, experimental data and statistical fitting. In this presentation, I describe how the modelling cycle works in the study of collective animal behaviour. Studies can be classified as addressing questions at different levels or linking different levels, i.e. as local, local to global, global to local or global. In addition, three distinct approaches are typically used – theory-driven, data-driven and model selection – to answer these questions. I will show with different examples how we move between these different levels of description and how these various approaches can be applied to link levels together.



4.1 Mining Candidate Causal Relationships

Matt Duckham (The University of Melborne, AU)

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Joint work of Bleisch, Susanne ; Duckham, Matt ; Galton, Antony ; Laube, Patrick ; Lyon, Jarod

Main reference S. Bleisch, M. Duckham, A. Galton, P. Laube, J. Lyon, "Mining candidate causal relationships in movement patterns," International Journal of Geographical Information Science, 28(2):363–382, 2014.

URL http://dx.doi.org/10.1080/13658816.2013.841167

The environmental context for, and drivers of movement patterns are arguably just as important as the patterns themselves. This research explores techniques for mining dense spatiotemporal data about the relationships between observed movement of objects and related environmental changes. The aim is to assist domain experts in identifying and testing hypotheses about possible causal relations between movement events and environmental events. The approach is based on a foundational model of the ontology of causation [1]. The raw environmental and movement data is categorized into sequences of atomic events experienced by each moving object over time. These events might include movement of an object from one place to another, or the start of an environmental event (e.g., the start of a high temperature even in the vicinity of a moving object). The output of the mining is an exhaustive set of frequent event sequences (candidate causal relationships), which can be ranked by support (the number of identified sequence as a proportion of all sequences). The analysis has been applied to real data about fish movement in the Murray River in Australia, helping to identify a number of expected and unexpected candidate causal relationships.

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4.2 A computation model of human navigation

Roland Geraerts (Utrecht University, NL)

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- Joint work of Geraerts, Roland; van Toll, Wouter; Jaklin, Norman;
- Main reference N. Jaklin, W. van Toll, R. Geraerts, "Way to go A framework for multi-level planning in games," in Proc. of the 3rd Int'l Workshop on Planning in Games (PG'13), pp. 11–14, 2013.
 URL http://icaps13.icaps-conference.org/wp-content/uploads/2013/05/pg13-proceedings.pdf
 - URL http://www.staff.science.uu.nl/~gerae101/pdf/Way_to_go_-_A_framework_for_multi-level_

planning_in_games.pdf

A huge challenge is to simulate tens of thousands of characters in real-time where they pro-actively and realistically avoid collisions with each other and with obstacles present in their environment. Such simulations are required for e.g. deciding whether crowd pressures do not build up too much during a festival, finding out how to improve crowd flow, training emergency personnel to deal with evacuation scenarios, or populating a game environment with realistic characters. This environment contains semantic information (e.g. roads and bicycle lanes, dangerous and pleasant areas), is three- dimensional (e.g. contains bridges where people can walk over and under as well) and can dynamically change (e.g. a bridge

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partially collapses). We currently study how to create a generic framework centered around a navigation mesh, for such environments and how it can be updated dynamically and efficiently. Next, we study how (groups of) people move and avoid collisions in such environments, based on character profiles and semantics. We run our simulations in realistic environments (e.g. soccer stadiums or train stations) and game levels to study the effectiveness of our methods. Finally, we have created a software package that integrates this research.

I gave a talk with the following messages:

- For simulating complex motions and behaviors, we need
 - = an abstract representation of the navigable areas;
 - = a framework of (at least) 5 complexity levels.
- Methods must be compatible with surface-based navigation at all levels (paradigm shift!), so a graph-based approach is not going to be sufficient
- A path planning algorithm should not compute a path
- Algorithms for complex motions have difficulties with force-based models
- Our simulation software is freely available for researchers

See http://www.staff.science.uu.nl/~gerae101/ for more information.

4.3 Flocking and turning of starling flocks

Asja Jelic (ISC-CNR - Rome, IT)

Joint work of Alessandro Attanasi, Andrea Cavagna, Lorenzo Del Castello, Irene Giardina, Tomas S. Grigera, Asja Jelic, Stefania Melillo, Leonardo Parisi, Oliver Pohl, Edward Shen, Massimiliano Viale

Turning flocks of starlings are a paradigm for a synchronized, rapid change of direction in moving animal groups. The efficiency of the information transfer during such a collective change of direction is the key factor to prevent cohesion loss and preserve robustness of a flock. However, the precise mechanism by which natural groups achieve such efficiency is currently not fully understood. I will present an experimental and theoretical study of starling flocks undergoing collective turns in which we analyze how the turning decision spreads across the flock. Using newly obtained 3D trajectories of every individual bird in a flock for the entire duration of a turning event, we find sound-like propagation with no damping of information. This is in contrast with standard theories of collective animal behavior based on alignment, which predict a much slower, diffusive spread of information. We propose a novel theory for propagation of orientation in flocks based on the rotational symmetries and conservation laws of the problem. The new theory also provides a quantitative prediction for the speed of propagation of the information, according to which transfer must be swifter the stronger the group's orientational order. This is confirmed by the experimental data. The link between strong order and fast transfer of information we found may be the adaptive drive for the high degree of behavioral polarization observed in many living groups.

4.4 Going with the flow: Towards In-Situ Human Behavior Modeling

Ko Nishino (Drexel University – Philadelphia, US)

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Computer vision research, in the past few decades, has made large strides toward efficient and reliable processing of the ever increasing video data, especially for surveillance purposes. Automated visual analysis of crowded scenes, however, remains a challenging task. As the number of people in a scene increases, nuisances that play against conventional video analysis methods surge. People will occlude each other, the notion of foreground and background collapses, and most important the behavior of the scene content especially of those of people will change to accommodate the clutter in the scene. These are nuisances not only to the computer algorithms but also to human operators that will have to squint through the clutter for hours and days to find a single adverse activity. In other words, automated video analysis is most needed in crowded scenes where it is hardest to do.

The crowd, however, does in turn give rise to invaluable visual cues regarding the scene dynamics. The appearance of a large number of people densely packed in the scene adds texture to the emerging movement of the people as a group–the crowd flow. If we can model the crowd flow while faithfully encoding their variability both in space and time, we may use it to extract important information about the dynamic scene. In this talk, I discussed about learning a statistical model of the spatially and temporally varying local motion patterns underlying the crowd flow and showed how we can use it to achieve challenging video analysis tasks, in particular anomaly detection and pedestrian tracking, in extremely crowded scenes.

4.5 How many insects does it take to make a swarm?

Nicholas Ouellette (Yale University, US)

Aggregations of social animals, such as flocks of birds, schools of fish, or swarms of insects, are beautiful, natural examples of self-organized behavior far from equilibrium. They tend to display a range of emergent properties, from enhanced sensing to the rapid propagation of information throughout the aggregate, that have made them a potentially valuable template for bio-inspired design. But how large must a group be before showing these emergent properties? I will address this question by presenting measurements of laboratory mating swarms of the non-biting midge *Chironomus riparius*. We measured swarms of various numbers of individuals and studied how their statistical properties changed with group size. Surprisingly, by about 10 individuals, all statistical properties of the swarms saturate. These results both provide a strong constraint on collective- motion models and also suggest that swarm robotics may indeed be feasible.

4.6 Model-based Segmentation and Classification of Trajectories

Stef Sijben (Ruhr-Universität Bochum, DE)

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 Joint work of Alewijnse, Sander P.A.; Buchin, Kevin; Buchin, Maike; Sijben, Stef; Westenberg, Michel A.
 Main reference S. P. A. Alewijnse, K. Buchin, M. Buchin, S. Sijben, M. A. Westenberg, "Model-based Segmentation and Classification of Trajectories," Extended Abstract of a presentation given at the 30th European Workshop on Computational Geometry (EuroCG'14), 4 pages, 2014.
 URL http://www.cs.bgu.ac.il/~eurocg14/papers/paper_36.pdf

We present efficient algorithms for segmenting and classifying a trajectory based on a parameterized movement model like the Brownian bridge movement model. Segmentation is the problem of subdividing a trajectory into parts such that each part is homogeneous in its movement characteristics. We formalize this using the likelihood of the model parameter. We consider the case where a discrete set of m parameter values is given and present an algorithm to compute an optimal segmentation with respect to an information criterion in O(nm) time for a trajectory with n sampling points. Classification is the problem of assigning trajectories to classes. We present an algorithm for discrete classification given a set of trajectories. Our algorithm computes the optimal classification with respect to an information criterion in $O(m^2 + mk(\log m + \log k))$ time for m parameter values and k trajectories, assuming bitonic likelihood functions.

4.7 Algorithms for Hotspot Computation on Trajectory Data

Frank Staals (Utrecht University, NL)

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 Main reference J. Gudmundsson, M. van Kreveld, F. Staals, "Algorithms for Hotspot Computation," in Proc. of the 21st ACM SIGSPATIAL Int'l Conf. on Advances in Geographic Information Systems (SIGSPATIAL'13), pp. 134–143, ACM, 2013.
 URL http://dx.doi.org/10.1145/2525314.2525359

We study one of the basic tasks in moving object analysis, namely the location of hotspots. A hotspot is a (small) region in which an entity spends a significant amount of time. Finding such regions is useful in many applications, for example in segmentation, clustering, and locating popular places. We may be interested in locating a minimum size hotspot in which the entity spends a fixed amount of time, or locating a fixed size hotspot maximizing the time that the entity spends inside it. Furthermore, we can consider the total time, or the longest contiguous time the entity spends in the hotspot. We solve all four versions of the problem. For a square hotspot, we can solve the contiguous-time versions in $O(n \log n)$ time, where n is the number of trajectory vertices. The algorithms for the total-time versions are roughly quadratic. Finding a hotspot containing relatively the most time, compared to its size, takes $O(n^3)$ time. Even though we focus on a single moving entity, our algorithms immediately extend to multiple entities. Finally, we consider hotspots of different shape.

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4.8 The dilemma of foraging in a group, studied by on-board audio and GPS monitoring of bats in the wild

Yossi Yovel (Tel Aviv University, IL)

How animals move and forage in the presence of conspecifics is one of the most fundamental questions in social behavior. Even though bats account for more than a fifth of mammalian species, they are very hard to monitor in the wild because of their small size and their agile nocturnal behavior. Here, we present a new system which allows full night monitoring of an echolocating bat's movement and foraging activity. We mount bats with miniature devices which include GPS and an ultrasonic microphone. This system takes advantage of the bat's reliance on active sensing (echolocation) which requires emitting sound to perceive the environment. The setup thus allows studying how bats forage with conspecific competition. For the first time, we tracked bats flying along hundreds of kilometers in the wild while following their foraging behavior. Data shows that bats group and are attracted to conspecifics but that their foraging success decreases when they are too close to each other. We show that the decrease in foraging does not result from sensory jamming by the echolocation of other bats, as has been previously suggested, but from the need to localize other bats in order to avoid collision. We therefore found strong evidence for the existence of a classical group foraging dilemma between the need to forage together to improve success and the need to keep a distance apart to avoid interference.

5 Working Groups

5.1 Collective Behaviour and Interactions with the Environment

Edward A. Codling (University of Essex, GB)

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 Joint work of Codling, Edward A.; Geraerts, Roland; Löffler, Maarten; Nishino, Ko; Perna, Andrea; Yovel, Yossi

The working group considered the open problem of how to determine the role and extent of environmental interactions in collective group behaviour and movement. The group considered the open problem from different perspectives and discussed more specific open questions such as "How can one determine important landscape features or the distribution of an unknown resource given known group behavioural rules and group movement data?". Or "How can one determine the most efficient set of behavioural rules for the collective group in order to maximise the utilisation of a known resource or minimise the time taken to move through a known landscape?". The group discussed various techniques and approaches that could be used to address these open questions. Some of these approaches require novel methodology and the development of such tools was discussed within the group. The group considered how to address the open problem in the specific context of groups of foraging bats. In addition, wider contexts for the open problem were also considered. Examples include better understanding of human crowd behaviour in urban landscapes, improved algorithms for simulated agents in computer games, and general ecological problems such as migration and navigation of schools of fish or flocks of birds. While the open problems considered were not solved directly during the workshop, the group made some useful progress in designing

a conceptual framework for further study. Members of the working group have agreed to continue collaborating on the open problems considered at the workshop and this may lead to future publications.

5.2 Dynamic Behaviour Indices to Explore Movement of a Goose Family Group

Andrea Kölzsch (MPI für Ornithologie – Radolfzell, DE)

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Being initiated by the general interest on dynamic social movement analyses, this group focused on discussing possible data analyses for a data set of high resolution GPS positions and accelerometer measures of a family of geese in their breeding grounds. A main point of interest was how to extract dynamic leadership from the data and test if goose parents were indeed leading the chicks. First, the group discussed previously used methods that had been used to determine leadership in large flocks of e.g. fish, starlings or pigeons. It became clear that in those studies coordinated turning of the animals was a main property exploited to determine leadership. For the goose tracks, however, such turning events were very infrequent and less pronounced. Thus, other possibilities of identification of critical events are needed, and we discussed the possibilities of using distance, speed, direction or behavioral states. Second, we tested some of our ideas on the goose data set (2 parents + 5 chicks, one day) that was provided for this workshop. It became apparent that the data had several weaknesses that the data owners had not been aware before, ranging from gaps at night for some individuals to shifts in time alignment. Exploration of the GPS and accelerometer data sets led to initial insights in the differences of behaviour of the different members of the goose family by e.g. speed and energy spent. A first idea of leadership by spatial position within the family was implemented and seemed a promising way forward for further investigations. Future collaboration ideas were discussed within the group. We aim to (i) improve data visualization methods for small groups of animals moving in a coordinated way, (ii) explore mathematical properties of and use methods for analysis of accelerometer data of animal groups and (iii) develop leadership indices by position rather than turning.

5.3 Subgroup Coordination

Ran Nathan (The Hebrew University of Jerusalem, IL)

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Studies of collective movement commonly assume that all individuals are identical. This assumption simplifies investigating the most basic properties of collective movement itself, that is, those arising from the tendency of individuals to move together. Yet, real-life individuals often differ in various important features, including size, sex or social ties, as well as being from different species identity. These difference could impact the way each individual

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perceives its neighbors, and hence alter their decisions how, when and where to go. For example, many collective movement systems involve social groups in which several features of the social structure, such as dominance and various associations, could play a key role in shaping the resulting movement patterns. Basic models developed to investigate collective movement show how collective motion can arise from simple rules and local interactions, such as repulsion, alignment and attraction. A much smaller set of studies have relaxed the assumption of identical individuals, demonstrating how variation in social identity can affect the movement patterns of individuals within the group, and the entire group itself. Preference to move near certain other individuals, can give rise to spatiotemporal subgroups within a group. Subgroups prevail in human crowds, and are crucial for understanding and modeling the behavior of the pedestrians. Overall, although subgroups occur in many systems of social animals, they have been scarcely incorporated in modeling and empirical studies of animal collective movement.

In this group, we discussed some key challenges in studying subgroup coordination, such as rather ambiguous terminology and lack of basic concepts. We also discussed the use of several possible indices (e.g. Simpson's diversity index) and algorithms (e.g. reparameterization surface) to identify subgroups, and how to develop null models for this purpose (e.g. randomized trajectories around the mean center-of-mass path). We shared movement tracks of 5 flocks of jackdaws, for which subgroup coordination is expected given the known pair-based linear social hierarchy in this species. Practically, we set a goal of preparing a joint synthesis paper highlighting this topic for scholars of animal movement, and set specific writing tasks among group members.

5.4 On the Quality of Trajectory Data, Trajectory Analysis, and Trajectory Cleaning

Frank Staals (Utrecht University, NL)

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 Joint work of Blanke, Ulf; van Kreveld, Marc; van der Spek, Stefan; Staals, Frank; Tredan, Gilles; Wenk, Carola

In the two working group sessions we discussed two related topics: (i) the quality of trajectory data and its influence on the quality of the analysis, and (ii) the role of cleaning the data, e.g. removal of outliers etc, on the analysis.

Quality of Trajectory Data and its Analysis. We started by identifying properties and characteristics of (loss in) the quality of trajectory data. We identified different kinds of errors in trajectory data (e.g. lack of geometric precision, missing data-points, etc.), and in its analysis. We discussed how to measure the quality of both trajectory data, and analysis tasks on trajectories. Furthermore, we considered a typical "pipeline" for the analysis of trajectory data in a GIS setting, in which we identified where these types of errors show up. We discussed how the quality of the data influences the quality of those steps in the analysis, and how this propagates to subsequent steps.

Cleaning Trajectory Data. From discussions with the workshop participants that worked with real trajectory data it became clear that for virtually any analysis task some "data cleaning" is required, e.g. detection and removal of outliers, removing trajectories with too few data points, etc. We discussed how to measure the amount of cleaning that has been done, and is still "required". Finally, we considered the quality of the analysis as a function

Maike Buchin, Luca Giuggioli, Marc van Kreveld, and Guy Theraulaz

of the amount of cleaning that has been done. We investigated the desired shape of such a function, and how to formalize this.

While we did not solve a concrete problem during the workshop, we have made some interesting observations on the topic of "quality and trajectories". We continue to work on this, and expect it will lead to future publications.

6 Concluding Remarks

On Friday afternoon the participants reviewed the seminar and discussed potential followup seminars. All participants enjoyed the interdisciplinarity of the seminar. Several participants mentioned that they were unaware of the research and results in different fields, yet relevant for their own work. Therefore, a number of interdisciplinary collaborations have started up. While all participants would be happy to return to a similar seminar later, it was agreed that the focus will slightly shift to keep this cross-fertilization of the different research fields.



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Report from Dagstuhl Seminar 14141

Reachability Problems for Infinite-State Systems

Edited by

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— Abstract

This report documents the program and the outcomes of Dagstuhl Seminar 14141 "Reachability Problems for Infinite-State Systems", held from March 30th until April 4th, 2014. The seminar gathered 44 participants and the program consisted of 34 presentations. Participants were asked to contribute open questions prior and during the seminar. A list of these open questions appears in a separate section of the present report. This list generated collaborations among participants and gave rise to research publications solving (partially), for example, question 5.13, namely "what functions are computable by VASS?"

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Many standard verification problems can be rephrased as reachability problems, and there exist powerful methods for determining reachability in infinite-state systems. However, applications require not only decidability results, but provably optimal algorithms. The seminar focussed on complexity and algorithmic issues for the verification of infinite-state systems, with special emphasis on reachability problems.

Verification of finite-state systems can be illustrated by considering the case of counter systems, i.e., computational models combining a finite-state control with counters. Counter systems have been used to model distributed protocols, programs with recursive parallel threads, programs with pointers, broadcast protocols, replicated finite-state programs, asynchronous programs, etc. If zero-tests are allowed – one speaks of "Minsky machines" –, counter systems have the power of Turing machines, and so all their verification problems



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are undecidable. On the other hand, many problems can be decided when zero-tests are forbidden – one speaks of VASS, for "vector addition systems with states", or equivalently "Petri nets". In particular, reachability for VASS was shown decidable in 1982, and this can be leveraged into many more positive results. Moreover, researchers developed techniques that, while necessarily incomplete, allow analysing many questions: reversal-bounded analysis à la Ibarra, accelerations à la FAST, or well-structured extensions of VASS, see e.g., the forward analysis procedure. In turn, these techniques have led to many new theoretical results. For instance, it has been shown that the reachability sets of both reversal-bounded counter automata and flat counter automata are effectively definable in Presburger arithmetic (assuming some additional conditions).

The seminar addressed the following topics:

- Complexity of reachability on various models: parameterized counter systems, lossy channel systems, lossy counter systems, at counter systems, reversal-bounded counter systems, and other.
- Decidability and complexity of reachability problems for Petri nets extensions: timed Petri nets, Petri nets with one zero-test, with one unbounded counter, linear dynamical systems, BVASS, data nets, and other.
- Recent development and uses of the theory of well-structured transition systems.
- Decidability and complexity of reachability for systems with multiple (constraints) stacks: multiphase, reversal-bounded, and other.
- Games on infinite-state systems: counter automata, timed systems, weighted automata. Games with energy constraints.
- Monadic logics with costs.
- New developments in the algorithmics of Presburger logics; SMT-solvers.

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3.1 Cut-offs on Parameterized Systems

Parosh Aziz Abdulla (Uppsala University, SE)

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We present a simple and efficient framework for automatic verification of systems with a parameteric number of communicating processes.

The processes may be organized in various topologies such as words, multisets, rings, or trees.

Our method needs to inspect only a small number of processes in order to show correctness of the whole system. It relies on an abstraction function that views the system from the perspective of a fixed number of processes. The abstraction is used during the verification procedure in order to dynamically detect cut-off points beyond which the search of the state space need not continue.

Our experimentation on a variety of benchmarks demonstrate that the method is highly efficient and that it works well even for classes of systems with undecidable verification problems. (*Preliminary abstract, March 30 2014*)

3.2 Timed Pushdown Automata

problems are EXPTIME-complete.

Mohamed Faouzi Atig (Uppsala University, SE)

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 Joint work of Abdulla, Parosh Aziz; Atig, Mohamed Faouzi; Stenman, Jari
 Main reference P. A. Abdulla, M. F. Atig, J. Stenman, "Zenoness for Timed Pushdown Automata," in Proc. of the 15th Int'l Workshop on Verification of Infinite-State Systems (INFINITY'14), EPTCS, Vol. 140, pp. 35–47, 2014.

 URL http://dx.doi.org/10.4204/EPTCS.140.3

Timed pushdown automata are pushdown automata extended with a finite set of real-valued clocks. Additionally, each symbol in the stack is equipped with avalue representing its age. The enabledness of a transition may depend on the values of the clocks and the age of the topmost symbol. Therefore, dense-timed pushdown automata subsume both pushdown

3.3 The Linear Ranking-Function Problem For Linear-Constraint Loops with a Precondition

automata and timed automata. In this talk, I will show that the reachability and zenoness

Amir M. Ben-Amram (Academic College of Tel Aviv, IL)

The linear ranking-function problem for (single-path) linear-constraint loops has been wellstudied and its complexity established for loop that compute over integers or over the rational numbers. That is, when one assumes that any initial state is possible. What if one is also given part of the initial state? Then the problem is much harder. I can prove some lower bounds but it is not known if the problems are even decidable.

3.4 Handling Infinitely Branching WSTS

Michael Blondin (ENS Cachan, FR and Université de Montréal, CA)

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 Joint work of Blondin, Michael; Finkel, Alain; McKenzie, Pierre
 Main reference M. Blondin, A. Finkel, P. McKenzie, "Handling Infinitely Branching WSTS," in Proc. of the 41st Int'l Colloquium on Automata, Languages, and Programming (ICALP'14), LNCS, Vol. 8573, pp. 13–25, Springer, 2014.
 URL http://dx.doi.org/10.1007/978-3-662-43951-7_2

Most decidability results concerning well-structured transition systems apply to the finitely branching variant. Yet some models (inserting automata, omega-Petri nets, ...) are naturally infinitely branching. Here we develop tools to handle infinitely branching WSTS by exploiting the crucial property that in the (ideal) completion of a well-quasi-ordered set, downwardclosed sets are finite unions of ideals. Then, using these tools, we derive decidability results and we delineate the undecidability frontier in the case of the termination, the controlstate maintainability and the coverability problems. A new forward algorithm for deciding coverability is obtained and boundedness is also shown decidable.

3.5 Symbolic Hybrid Transduction

Bernard Boigelot (Université de Liège, BE)

This work addresses the exact computation of the set of reachable configurations of systems modeled by linear hybrid automata. The contribution is an original approach to accelerating control cycles, which consists in computing symbolically the effect of iterating such cycles any number of times. This is achieved by first modeling the data transformation labeling a cycle as a Linear Hybrid Relation, which is a set of linear constraints describing the transformation applied to the variables when this cycle is followed. A LHR maps individual variable values onto a set corresponding to a convex polyhedron in *n*-dimensional space, and such a polyhedron into a polyhedron of the same form. We introduce a data structure called linear hybrid transducer that represents a LHR and makes it possible to reason about the possible transformations that such a LHR induces on polyhedra. Accelerating a LHR can then be performed by computing symbolically the transitive closure of its corresponding linear hybrid transducer. This effectively reduces the acceleration of LHR to a purely discrete problem.

3.6 Sets with Atoms

Mikolaj Bojańczyk (University of Warsaw, PL)

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 Joint work of Bojańczyk, Mikolaj; Slawomir Lasota; Bartek Klin; Luc Segoufin; Szymon Toruńczyk; Joanna Ochremiak
 URL http://atoms.mimuw.edu.pl

The talk is about sets with atoms, and how they can be used to compute some things about infinite sets. Included in the talk is a demonstration of a tool, written by Eryk Kopczynski, which allows one to compile and run the following program.

```
for every rational numbers x, y, z
if (x < y) and (y < z) and not (x < z) then print ''error''
```

The program does not print "error". In general, instead of the rational numbers, there can be any logical structure with a decidable first-order theory. The tool is an implementation, and a theoretical extension, of a programming language for sets with atoms.

3.7 On the Hardness of Solving Ordinary Differential Equations

Olivier Bournez (École Polytechnique – Palaiseau, FR)

We prove that a particular class of ordinary differential equations (ordinary differential equations with polynomial right hand side) can be solved in polynomial time.

We prove that conversely that polynomial time can be characterized by ordinary differential equations with polynomial right hand side.

This yields both an implicit characterization of polynomial time in terms of ordinary differential equations, and a completeness result on the reachability problems for the corresponding class. (*Preliminary abstract, March 30 2014*)

3.8 Zero-Reachability in Probabilistic Multi-Counter Automata

Tomas Brazdil (Masaryk University – Brno, CZ)

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We study the qualitative and quantitative zero-reachability problem in probabilistic multicounter systems. We identify the undecidable variants of the problems, and then we concentrate on the remaining two cases. In the first case, when we are interested in the probability of all runs that visit zero in some counter, we show that the qualitative zeroreachability is decidable in time which is polynomial in the size of a given pMC and doubly exponential in the number of counters. In the second case, when we are interested in the probability of all runs that visit zero in some counter different from the last counter, we show that the qualitative zero-reachability is decidable. In both cases we show that the probability of all zero-reaching runs can be effectively approximated up to an arbitrarily small given error $\epsilon > 0$. (*Preliminary abstract, March 30 2014*)

3.9 Secure Equilibria in Weighted Games

Véronique Bruyère (University of Mons, BE)

 $\begin{array}{c} \mbox{License} \ensuremath{\mbox{\footnotesize \mbox{$ \odot$} $}} \end{array} \mbox{Creative Commons BY 3.0 Unported license} \\ \ensuremath{\mbox{$ \odot$} $} \ensuremath{\mbox{$ V$}\ensuremath{\mbox{$ \circ$} $}} \ensuremath{\mbox{$ \circ$} $} \ensuremath{\mbox{$ \circ$$

We consider two-player non zero-sum infinite duration games played on weighted graphs. We extend the notion of secure equilibrium introduced by Chatterjee et al., from the Boolean setting to this quantitative setting. As for the Boolean setting, our notion of secure equilibrium refines the classical notion of Nash equilibrium. We prove that secure equilibria always exist in a large class of weighted games which includes common measures like sup, inf, lim sup, lim inf, mean-payoff, and discounted sum. Moreover we show that one can synthesize such strategy profiles that are finite-memory and use few memory. We also prove that the constrained existence problem for secure equilibria is decidable for sup, inf, lim sup, lim inf and mean-payoff measures. Our solutions rely on new results for zero-sum quantitative games with lexicographic objectives that are interesting on their own right.

3.10 Infinite-state Model Checking with Data Recycling

Giorgio Delzanno (University of Genova, IT)

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We present a model checking algorithm for infinite-state systems based on a garbage collection procedure for dynamically recycling unused data representations. The goal of data recycling is to maintain within a finite range the set of representations of distinct values needed for a complete state space exploration. The verification procedure takes inspiration from recent decidability results obtained for classes of data-centric systems with dynamic generation of fresh data. We have implemented a prototype version of the algorithm using the Spin model checker and applied it to some classical examples of concurrent systems with unbounded data, like Lamport's bakery and ticket mutual exclusion protocols with a fixed number of process instances. (Preliminary abstract, March 30 2014)

3.11 Reachability in Partial-Observation Stochastic Games

Laurent Doyen (ENS Cachan, FR)

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    Joint work of Doyen, Laurent; Chatterjee, Krishnendu
    Main reference K. Chatterjee, L. Doyen, "Partial-Observation Stochastic Games: How to Win when Belief Fails,"

            in Proc. of the 27th Annual IEEE Symp. on Logic in Computer Science (LICS'12), pp. 175–184,

            IEEE, 2012; pre-print available as arXiv:1107.2141 [cs.GT].

    URL http://dx.doi.org/10.1109/LICS.2012.28
        URL http://arxiv.org/abs/1107.2141v1
```

The talk presents a quick survey of the main results about the complexity of two-player partial-observation finite-state stochastic games with a reachability objective (as well as some subclasses and extensions).

While several (recent) results have enriched our knowledge about this framework, it is not known whether the existence of a winning strategy is decidable for reachability games with pure strategies.

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Special cases of this problem are decidable, and show that the memory requirement is at least non-elementary (tower of exponentials) although the games are finite-state and with a simple reachability objective (and finite memory is sufficient).

This surprising result has connections with difficult problems for certain classes of counter systems. The talk glances through this connection and open problem.

3.12 Resoning About Data Repetitions with Counter Systems

Diego Figueira (University of Edinburgh, GB)

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 Joint work of Demri, Stéphane; Figueira, Diego; Praveen, M.
 Main reference S. Demri, D. Figueira, M. Praveen, "Reasoning about Data Repetitions with Counter Systems," in Proc. of the 28th Annual ACM/IEEE Symp. on Logic in Computer Science, pp. 33–42, IEEE, 2013.
 URL http://dx.doi.org/10.1109/LICS.2013.8

We study linear-time temporal logics interpreted over data words with multiple attributes. We demonstrate correspondences between satisfiability problems for logics and reachability-like decision problems for counter systems. We show that allowing/disallowing atomic formulas expressing repetitions of values in the past corresponds to the reachability/coverability problem in Petri nets. This gives us 2-EXPSPACE upper bounds for several satisfiability problems. We prove matching lower bounds by reduction from a reachability problem for a newly introduced class of counter systems. This new class is a succinct version of vector addition systems with states in which counters are accessed via pointers, a potentially useful feature in other contexts. We strengthen further the correspondences between data logics and counter systems by characterizing the complexity of fragments, extensions and variants of the logic.

3.13 The VJGL Lemma

Jean Goubault-Larrecq (ENS Cachan, FR)

The VJGL Lemma generalizes a famous useful theorem by Valk and Jantzen (1985). It allows one to compute finite bases of upward closed subsets U of well-quasi-ordered sets X under two simple assumptions: the so-called effective complement property, and the assumption that it is decidable whether a given element of the completion of X meets U. We give a short proof of it, and applications to several (in fact infinitely many) well-quasi-ordered sets. The effective complement property is true in all these cases.

3.14 Temporal Logics and Automata on Multi-attributed Data Words with Ordered Navigation

Peter Habermehl (Université Paris-Diderot, FR)

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We study temporal logics and automata on multi-attributed data words. Recently, BD-LTL was introduced as a temporal logic on data words extending LTL by navigation along

Javier Esparza, Alain Finkel, Pierre McKenzie, and Joel Ouaknine

positions of single data values. It is known that allowing for navigation wrt. tuples of data values renders the logic undecidable. We therefore introduce ND-LTL, an extension of BD-LTL by tuple-navigation that is only restricted in terms of a certain order on the attributes. While complete ND-LTL is still undecidable, the two natural fragments allowing for either future or past navigation along data values are shown to be Ackermann-hard, yet decidability is obtained by reduction to nested multi-counter systems. To this end, we introduce and study nested variants of data automata as an intermediate model simplifying the constructions. Interestingly, on BD-LTL, the same restrictions have a significant impact on the decision procedure. While satisfiability of BD-LTL is as hard as reachability in Petri nets, our restrictions yield two 2-EXPSPACE-complete fragments. (*Preliminary abstract, March 30 2014*)

3.15 Subclasses of Presburger Arithmetic and the Weak EXP Hierarchy

Christoph Haase (ENS Cachan, FR)

I will show that for any fixed i > 0, the Σ_{i+1} -fragment of Presburger arithmetic, i.e., its restriction to i + 1 quantifier alternations beginning with an existential quantifier, is complete for the i^{th} level of the weak EXP hierarchy. This result completes the computational complexity landscape for Presburger arithmetic, a line of research which dates back to the seminal work by Fischer & Rabin in 1974. Moreover, I will discuss bounds on sets of naturals definable in the existential fragment of Presburger arithmetic: given an existential formula p(x), I will show that the set of solutions is an ultimately periodic set whose period can be doubly-exponentially bounded from below and above.

3.16 Reachability Problems are NP-complete for Flat Counter Systems with Octagonal Loops

Radu Iosif (VERIMAG - Gières, FR)

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 Joint work of Iosif, Radu; Bozga, Marius; Konecny, Filip
 Main reference M. Bozga, R. Iosif, F. Konecny, "Safety Problems are NP-complete for Flat Integer Programs with Octagonal Loops," arXiv:1307.5321v3 [cs.CC], 2013.
 URL http://arxiv.org/abs/1307.5321v3

This paper proves the NP-completeness of the reachability problem for the class of flat counter machines with difference bounds and, more generally, octagonal relations, labeling the transitions on the loops. The proof is based on the fact that the sequence of powers of such relations can be encoded as a periodic sequence of matrices, and that both the prefix and the period of this sequence are simply exponential in the size of the binary encoding of the relation. This result allows to characterize the complexity of the reachability problem for one of the most studied class of counter machines, and has a potential impact for other problems in program verification.

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3.17 Equivalences of Deterministic Systems as Reachability Problems

Petr Jančar (TU – Ostrava, CZ)

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In a labelled transition system (LTS), a pair (s, t) of states is in the trace-preorder if each trace (a sequence of actions) that is enabled by s is also enabled by t. States s, t are trace-equivalent if both (s, t) and (t, s) are in the trace preorder. For a deterministic LTS L, the complement of the trace-preorder problem can be naturally formulated as a reachability problem in the product deterministic LTS $L \times L$: (s, t) is not in the trace-preorder if there is a pair (s', t')that is reachable from (s, t) and where s' enables an action that is not enabled by t'. We focus on these (reachability) problems for deterministic pushdown automata (DPDA) where the trace-preorder is undecidable while the trace-equivalence is known to be in TOWER. The precise complexity of the latter remains a challenging problem, since only P-hardness is known regarding the lower bound.

3.18 Analysis of Probabilistic Parallel Processes

Stefan Kiefer (University of Oxford, GB)

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    Joint work of Bonnet, Remi; Kiefer, Stefan; Lin, Anthony W.
    Main reference R. Bonnet, S. Kiefer, A. W. Lin, "Analysis of Probabilistic Basic Parallel Processes," in Proc. of the 17th Int'l Conf. on Foundations of Software Science and Computation Structures (FOSSACS'14), LNCS, Vol. 8412, pp. 43–57, Springer, 2014.
    URL http://dx.doi.org/10.1007/978-3-642-54830-7_3
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Basic Parallel Processes (BPPs) are a well-known subclass of Petri Nets. They are the simplest common model of concurrent programs that allows unbounded spawning of processes.

In the probabilistic version of BPPs, every process generates other processes according to a probability distribution. We study the decidability and complexity of fundamental qualitative problems over probabilistic BPPs – in particular reachability with probability 1 of different classes of target sets (e.g. upward-closed sets).

Our results concern both the Markov-chain model, where processes are scheduled randomly, and the MDP model, where processes are picked by a scheduler.

3.19 Well-Structured Graph Transformation Systems

Barbara König (Universität Duisburg-Essen, DE)

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Barbara König
Joint work of König, Barbara; Stueckrath, Jan

Graph transformation systems (GTSs) can be seen as well-structured transition systems (WSTSs), thus obtaining decidability results for certain classes of GTSs. It was shown that well-structuredness can be obtained using the minor ordering as a well-quasi-order. We extend this idea to obtain a general framework in which several types of GTSs can be seen as (restricted) WSTSs. We instantiate this framework with the subgraph ordering and the induced subgraph ordering. Furthermore we present the tool UNCOVER and discuss runtime results.

Javier Esparza, Alain Finkel, Pierre McKenzie, and Joel Ouaknine

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3.20 **Adversarial Patrolling Games**

Antonín Kučera (Masaryk University – Brno, CZ)

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Patrolling is one of the central problems in operational security. Formally, a *patrolling* problem is specified by a set U of vulnerable targets and a function d which to every target uassigns the time $d(u) \in N$ needed to complete an intrusion at u. The goal is to design an optimal strategy for a *defender* who is moving from target to target and aims at detecting possible intrusions. The defender can detect an intrusion at u only by visiting u before the intrusion is completed. The goal of the *attacker* is to maximize the probability of a successful attack. We assume that the attacker is *adversarial*, i.e., he knows the strategy of the defender and can observe her moves. We assume that all targets are equally important and that each move from target to target takes one unit of time. The set of admissible moves is specified by an *environment* $E \subseteq U \times U$, where the fully connected digraph (incl. all loops) models the unrestricted environment.

We prove that the defender has an optimal strategy for every patrolling problem and every environment. Then, we give an upper bound for the Stackelberg value, i.e., the maximal probability of successfully defended attacks that can be achieved by the defender against an arbitrary strategy of the attacker. The bound is valid for an arbitrary environment. Further, we show that if for every attack length k the total number of all targets u with d(u) = kis divisible by k, then the bound is achievable in the unrestricted environment by a simple modular strategy of the defender which is computable in polynomial time. We also give an exact classification of all sufficiently connected environments E where the bound is achievable - we show that there is a *characteristic digraph* computable in polynomial time such that E is sufficiently connected if and only if it contains a subdigraph isomorphic to the characteristic digraph. Hence, the problem whether a given environment is sufficiently connected is in NP, and we provide a matching lower bound which is valid also for restricted subclasses of patrolling problems.

Turing Machines Over Infinite Alphabets 3.21

Slawomir Lasota (University of Warsaw, PL)

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Main reference M. Bojańczyk, B. Klin, S. Lasota, S. Torunczyk, "Turing Machines with Atoms," in Proc. of the 28th Annual ACM/IEEE Symposium on Logic in Computer Science (LICS'13), pp. 183–192, IEEE CS. 2013.

URL http://dx.doi.org/10.1109/LICS.2013.24

In sets with atoms, finiteness is relaxed to "finiteness up to permutation", known as orbitfiniteness. The talk will be devoted to Turing machines where state space, input alphabet and transition relation are orbit-finite. We will focuson two main results.

First, we show that deterministic machines are weaker than nondeterministic ones; in particular, P is not equal NP in sets with atoms. The separating language is closely related to the Cai-Fuerer-Immerman graphs used in descriptive complexity theory. The second result is an effective characterization of those input alphabets for which Turing machines determinize (called standard alphabets). To this end, the determinization problem is expressed as a Constraint Satisfaction Problem, and a characterization is obtained from deep results in CSP theory.

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3.22 Non-Elementary Complexities for Branching VASS, MELL, and Extensions

 Ranko Lazić (University of Warwick, GB)
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 Joint work of Lazić, Ranko; Schmitz, Sylvain
 Main reference R. Lazić, S. Schmitz, "Non-Elementary Complexities for Branching VASS, MELL, and Extensions," arXiv:1401.6785v1 [cs.LO], 2014.
 URL http://arxiv.org/abs/1401.6785v1

We study the complexity of reachability problems on branching extensions of vector addition systems, which allows us to derive new non-elementary complexity bounds for fragments and variants of propositional linear logic. We show that provability in the multiplicative exponential fragment is Tower-hard already in the affine case – and hence non-elementary. We match this lower bound for the full propositional affine linear logic, proving its Tower-completeness. We also show that provability in propositional contractive linear logic is Ackermann-complete.

3.23 Vector Addition System Toolbox

Jerôme Leroux (Université de Bordeaux, FR)

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Vector addition systems, a class equivalent to the Petri nets, form a well-known class of models with many decidable properties. In this presentation, we present a well partial order on runs. This partial order is shown to be central for deriving many simple proof of decidability for various problems.

3.24 Deciding Coverability in Non-Monotone Infinite-State Systems

Richard Mayr (University of Edinburgh, GB)

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 Joint work of Mayr, Richard; Abdulla, Parosh Aziz
 Main reference P. A. Abdulla, R. Mayr, "Priced Petri Nets," Logical Methods in Computer Science, 9(4):10, 51 pages, 2013.

 URL http://dx.doi.org/10.2168/LMCS-9(4:10)2013

We describe a general construction for solving reachability/coverability problems for infinitestate systems under some weak abstract conditions. In particular, we do not assume that the behavior of these systems is fully monotone w.r.t. some well-quasi-order, unlike in many related works on well-structured/well-quasi-ordered transition systems (e.g., Abdulla et al., Finkel et al.). This technique, called the phase construction, has been described in [1, 2, 3] and instantiated to solve a question about infinite-state real-time systems. However, it is fully abstract and can be instantiated in many different ways. We think that this technique deserves to be more widely known, since it can be useful for other people working in the field of infinite-state system verification. In particular, it includes a technique for computing the minimal elements of upward-closed sets in arbitrary well-quasi-ordered domains. This is the most general form of the Valk-Jantzen construction in arbitrary well-quasi-ordered domains, as described in [1, 2].

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3.25 Decision Problems for Discrete Linear Dynamical Systems: A Survey

Joel Ouaknine (University of Oxford, GB)

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Joint work of Ouaknine, Joel; Worrell, James
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I will survey the state of the art regarding decision problems for discrete linear dynamical systems, including the Skolem Problem, the Positivity and Ultimate Positivity problems for linear recurrence sequences, the Orbit and Polyhedron-hitting problem, etc. I will also discuss applications to verification, e.g. the termination of simple linear loops and reachability and invariance in Markov chains.

3.26 Software Model Checking via Petri Net Language Inclusion

Andreas Podelski (Universität Freiburg, DE)

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We present an approach to software model checking for parametrized concurrent programs. In this approach, one reduces the validity of a candidate proof to checking the inclusion between two Petri net languages (which is checked via non-reachability).

We then extend the approach to the case where the proof needs to account for the local variables of each of the threads in a parametrized concurrent program. Here, one reduces the validity of a candidate proof to checking the inclusion between two languages recognized by a kind of data automata. The inclusion is decidable thanks to an argument based on well-quasi orderings.

The open problem is to extend the approach to parametrized concurrent programs where the proof needs to account for the relation between local variables of threads.

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3.27 Reachability Problems for Braids, Knots and Links – New Challenges for Computer Science

Igor Potapov (University of Liverpool, GB)

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In this talk I will introduce a few challenging reachability problems in computational topology opening new connections between mathematical knots, braid groups, combinatorics on words, words over infinite alphabets, complexity theory and provide solutions for some of these problems by application of several techniques from automata theory, matrix semigroups and algorithms.

3.28 Unordered Data Nets Are as Hard as Lossy Channel Systems

Fernando Rosa-Velardo (University Complutense of Madrid, ES)

We characterize the exact ordinal-recursive complexity of Unordered Data Nets (UDN), a subclass of Data Nets in which the data carried by tokens belong to an unordered domain. We use the techniques developed by Schmitz and Schnoebelen to bound the length of bad sequences in well-quasi orderings of finite multisets over tuples of naturals. These bounds imply hyper-Ackermannian upper bounds for the termination and the coverability problems for UDN. Then we prove that the previous bounds are tight, by constructing UDNs that weakly compute fast-growing functions and their inverses.

3.29 Complexity Hierarchies Beyond Elementary

Sylvain Schmitz (ENS Cachan, FR)

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 Main reference S. Schmitz, "Complexity Hierarchies Beyond Elementary," arXiv:1312.5686v2 [cs.CC], 2013. URL http://arxiv.org/abs/1312.5686v2

The talk first introduces a hierarchy of fast-growing complexity classes and show its suitability for completeness statements of many non elementary problems. This hierarchy allows the classification of many decision problems with a non-elementary complexity, which occur naturally in logic, combinatorics, formal languages, verification, etc., with complexities ranging from simple towers of exponentials to Ackermannian and beyond.

The second part of the talk gives a quick overview of so-called *length function theorem* for well-quasi-orders. These are combinatorial statements that provide explicit upper bounds on the length of *controlled* bad sequences over a given wqo.

3.30 Ackermann-hardness for Monotone Counter Systems

Philippe Schnoebelen (ENS Cachan, FR)

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 Main reference P. Schnoebelen, "Revisiting Ackermann-Hardness for Lossy Counter Machines and Reset Petri Nets," in Proc. of the 35th Int'l Symp. on Mathematical Foundations of Computer Science (MFCS'10), LNCS, Vol. 6281, pp. 616–628, Springer, 2010.

 URL http://dx.doi.org/10.1007/978-3-642-15155-2_54

We explain the key ideas behind the proof of Ackermann-hardness of reachability/coverability for Lossy Counter Machines, aka Lossy Minsky Machines.

The presentation follows the plan of Schnoebelen MFCS 2010 paper, with some recent minor simplifications like the use of Hardy functions.

3.31 Critical Exponents of *k*-automatic Words and Generalizations

Jeffrey O. Shallit (University of Waterloo, CA)

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A (fractional) repetition of exponent l/p is a word of length l and period p. For example, the French word **entente** is a repetition of exponent 7/3. The supremum over the exponents of all factors of an infinite word w is known as the critical exponent of w. Thue proved, for example, that the critical exponent of the Thue-Morse word is 2. In a recent paper with Luke Schaeffer, we showed that the critical exponent of k-automatic words is (i) rational or infinite and (ii) computable. Can a similar result be proved for some classes of infinite-state automata? For example, it is easy to see that the "ruler sequence" has critical exponent 2 and the "infinity series" of the Danish composer Per Nørgård has critical exponent 4/3.

3.32 Infinite Games and Reachability

Wolfgang Thomas (RWTH Aachen, DE)

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In this survey talk we present the fundamentals of the algorithmic theory of infinite games, starting with Church's Problem (1957), and emphasing the central role of reachability problems in the study of such games. The first part explains the solution of games defined by a requirement formulated in MSO-logic (Büchi-Landweber). This solution is obtained via a transformation of an MSO-formula into a finite-state game with the Muller winning condition, followed by a transformation into a parity game, which is then solved inductively, with an essential use of reachability games. In a second part we address two more recent tracks of research, the study of parity games over infinite arenas (in particular, pushdown graphs), and the approach of McNaughton to determine the winner of a finite-state game by a scoring process in the progress of a play, which results in a reduction of the problem to solving a reachability (or dually to a safety) game.

3.33 Models of the lambdaY-Calculus for Weak Monadic Second-Order Logic

Igor Walukiewicz (Université de Bordeaux, FR)

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 Joint work of Salvati Sylvain; Walukiewicz, Igor
 Main reference S. Salvati, I. Walukiewicz, "Models of the lambdaY-calculus for weak monadic second-order logic," unpublished manuscript.

LambdaY-calculus is simply typed lambda calculus with fixpoint operators. This calculus faithfully models control in higher-order programs. The semantic of a program represented by a lambdaY-term is a tree reflecting the control flow of the program.

We describe a model construction calculating properties of trees generated by lambdaYterms: the value of term in a model determines if the tree generated by the term has the given property. The construction works for all properties expressible in weak monadic second-order logic. This construction allows to obtain a (decidable) typing system for the model-checking problem. It gives a "verification by evaluation" approach to model-checking, and it opens a possibility of modular verification of large programs.

3.34 Ultimate Positivity is Decidable for Simple Linear Recurrent Sequences

James Worrell (University of Oxford, GB)

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We consider the decidability and complexity of the Ultimate Positivity Problem, which asks whether all but finitely many terms of a given rational linear recurrence sequence (LRS) are positive. Using lower bounds in Diophantine approximation concerning sums of S-units, we show that for simple LRS (those whose characteristic polynomial has no repeated roots) the Ultimate Positivity Problem is decidable in polynomial space. If we restrict to simple LRS of a fixed order then we obtain a polynomial-time decision procedure. As a complexity lower bound we show that Ultimate Positivity for simple LRS is at least as hard as the decision problem for universal sentences in the theory of real-closed fields. (*Preliminary abstract, March* 30 2014)

4 Open Problems

4.1 Linear-Ranking Function and Affine Functions

Amir M. Ben-Amram (Academic College of Tel Aviv, IL)

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4.1.1 Linear-Ranking Functions Problems

- What is the complexity of this group of problems (termination, LRF existence, LRF verification) for linear-constraint loops over the rationals? Over the integers?
- What are the complexities for affine-linear loops in either domain?
- What are other special cases of interest?
- Are the three problems above just as hard?

4.1.2 Affine Functions Problems

- In \mathbb{Z}^2 , I ask whether mortality decidable for functions of a restricted form, where "mortality" means that every iteration sequence (trajectory) reaches (0,0); and the functions in question are defined by dividing \mathbb{Z}^2 into a finite number of rectangular regions, i. e., by constraints of the form $x_1 \ge a, x_1 \le b, x_2 \ge c, x_2 \le d$ (some regions will be infinite, having no upper bound or no lower bound on one or both variables) and defining the function on each region by $f(x_1, x_2) = (x_1 + s, x_2 + t)$ where s, t depend on the region. One could also allow f to be defined to be zero on some regions.
- Over \mathbb{Z}^2 , consider a function class which is bigger than the above since one can also define $f(x_1, x_2) = (x_2 + s, x_1 + t)$ in some regions, i.e., switch the variables. Then mortality is shown undecidable in the paper; but it is a challending open problem to settle the decidability when the number of regions is bounded by a constant (even if this constant is as low as 7).
- Given an arbitrary affine-linear function with integer coefficients $f(x_1, \ldots, x_n)$, and a loop of the form while (Ax > b) do x := f(x) (here x ranges over \mathbb{Z}^n), is the loop mortal (universally terminating)?

4.2 Completion and Infinitely Branching WSTS

Michael Blondin (ENS Cachan, FR and Université de Montréal, CA)

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- What applications has the WSTS completion?
- Boundedness, coverability, strong termination, and strong control-state maintainability are decidable for infinitely branching WSTS under some assumptions. Are there other problems decidable? Under which assumptions?
- For what families of WSTS and for what problems are the algorithms working on the completion more efficient?

4.3 Symbolic Hybrid Transduction

Bernard Boigelot (Université de Liège, BE)

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- Could this approach be employed for computing directly the reachability set (instead of only accelerating a given control cycle)?
- Is it possible to decide whether the computation of the closure of a linear hybrid transducer will terminate or not?
- How can linear hybrid relations over a large number of variables be accelerated efficiently?

4.4 The VJGL Lemma

Jean Goubault-Larrecq (ENS Cachan, FR)

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- Can completions be used to analyze Kosaraju's algorithm in terms of the well-quasiordering on runs presented by Jérôme Leroux (with Sylvain Schmitz) on the first day of the seminar? The connection with bounded languages seems alluring. Here is why. The language L of traces of a Petri net is a subset of a set of words on a well-quasi-ordered alphabet A. The quasi-ordering looks very close to word embedding. We know that the completion of a poset of words with word embedding is a space of word-products, which are regular languages of a specific form, and which are certainly bounded. Is the completion of L of a similar form? Does it consist of bounded languages?
- The VJGL Lemma depends on showing the effective complement property for (effective) representations of elements of the completion. What would be such representations for graphs or hypergraphs under the minor embedding ordering, or other well quasi-orderings?

4.5 Subclasses of Presburger Arithmetic and the Weak EXP Hierarchy

Christoph Haase (ENS Cachan, FR)

4.5.1 Presburger arithmetic with divisibility

Lipshitz [2] has shown that the existential fragment of Presburger arithmetic with a full divisibility predicate is decidable. He moreover gave an outline of an NP upper bound in [3]. Can we find a complete rigorous proof of the NP bound?

4.5.2 The complexity of inclusion for context-free commutative grammars

Given context-free grammars G and H, is the Parikh image of G included in the Parikh image of H? This problem is known to be $\Pi_2^{\rm P}$ -hard and in NEXP [4]. If the size of the alphabet is fixed, the problem becomes $\Pi_2^{\rm P}$ -complete [5]. What is the precise complexity

of this problem when the alphabet is part of the input? Is there a syntactic fragment of Presburger arithmetic which yields an optimal upper bound of this problem?

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4.6 Equivalences of Deterministic Systems as Reachability Problems

Petr Jančar (TU – Ostrava, CZ)

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Can we improve the complexity gap described in the overview of the talk "Equivalences of deterministic systems as reachability problems"?

4.7 Turing machines over infinite alphabets

Slawomir Lasota (University of Warsaw, PL)

- Are standard alphabets closed under union?
- Is every deterministic TM equivalent to a deterministic TM whose work alphabet is the same as the input alphabet?
- Is there a natural NP-complete problem for TMs with atoms?

4.8 Branching VAS

Ranko Lazić (University of Warwick, GB)

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- The reachability problem for branching VAS is now known to be TOWER-hard, but decidability is still open.
- A clear Karp-Miller procedure for the top-down direction in branching VAS is currently missing.
- One could investigate decidability and complexity of checking regularity offree languages generated by branching VAS, in the top-down direction, and in thebottom-up direction.

4.9 Decision Problems for Discrete Linear Dynamical Systems

Joel Ouaknine (University of Oxford, GB)

This area is replete with open problems, many with applications to other areas such as software model checking. For example, the question of Universal Termination of integer linear problems in the general (i.e. non-homogeneous) case, as stated by Mark Braverman in [1]:

Consider the program:

WHILE $Bx > b do \{x := Ax + c\}$

where A, B are matrices and b, c are vectors, all over the integers.

Universal Termination is the assertion that this program terminates for all initial values of the vector of integer variables x. Decidability (for given A, B, b, c) is open.

References

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4.10 Rewriting Over Infinite Alphabets

Igor Potapov (University of Liverpool, GB)

Many computational processes can be described as rewriting systems over strings from a finite alphabet, where new words are generated following some rules for replacing, adding or deleting symbols. Nowadays there is a sufficiently broad research activity in the area of logic and automata for words and trees over infinite alphabets. It is many motivated by the need to analyse and verify infinite-state systems, which for example can use infinite alphabet of natural numbers $\{1, 2, 3, ...\}$ instead of finite number of symbols like $\{a, b, c\}$. In the seminal paper of M. Kaminski and N. Francez [1] a very restricted memory structure of the automaton (Register Automaton) working with words over infinite alphabets was introduced. The register automaton is operating by keeping a finite number of symbols (from the working tape) in its memory and making their comparison to other observed symbols. The model allows recognising a large class of languages over infinite alphabet and at the same time is not taking an advantage of its memory capabilities beyond what is needed for that purposes. A more complex system operating with words over infinite alphabet may require updating them in addition to the operations of comparison between symbols. Obviously, unrestricted and very general rules allowing rewriting over arbitrary infinite alphabet are too powerful making most of the computational problems to be undecidable. On the other hand there are existing fragments of rewriting systems over infinite alphabet with decidable word problem (i.e. algorithmic problem of deciding whether two given representatives represent the same element of the set). One of such example is unknotedness and equivalence of knots, where words over infinite alphabet are Gauss words (or Gauss diagrams) and the system of rewriting rules is a set of Reidemeister moves represented by insertion/deletion and swapping some of the symbols on Gauss words. While the set of the Reidemeister moves is quite powerful the

word problem for such rewriting rules on Gauss words is decidable following algorithms from combinatorial topology.

Open problems:

- Define the weakest rewriting rules over infinite alphabet with undecidable reachability problem (word problem).
- Define the most powerful (in computational sense) model of rewriting system over infinite alphabet with decidable reachability problem (word problem).
- Find upper/lower bounds on the length of reachability paths for rewriting systems over infinite alphabet with decidable reachability problem.

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4.11 Unordered Data Nets

Fernando Rosa-Velardo (University Complutense of Madrid, ES)

- Are UDN without broadcasts F_{ω}^{ω} -hard?
- What is the exact complexity of coverability and termination for
- Unordered Petri Data nets (UDN without broadcasts or whole-place operations)?
- Is reachability decidable for Unordered Petri Data nets?

4.12 Cichoń's Principle Redux

Sylvain Schmitz (ENS Cachan, FR)

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4.12.1 Summary

Under which conditions can one bound the maximal length of (g, n)-controlled bad sequences over a normed wqo $(A, \leq_A, |.|_A)$ with the Cichoń function $h_{o(A)}(n)$, where o(A) is the maximal ordertype of A and h is a "reasonable" function of g?

4.12.2 Length Function Theorems

We refer to [5] for details on controlled bad sequences and normed wqos. The reader will also find there one positive answer to the problem: for A built from finite sets using disjoint unions, Cartesian products, and Kleene star, the result holds with $h = p \circ g$ for a polynomial p. Another such answer was stated during the seminar: for $A = \alpha$ an ordinal less than ε_0 (and for a suitable norm), the maximal length is less than $g_{\alpha}(n)$. Of course one might want to consider other wqos, in particular with maximal order types higher than ε_0 .

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4.12.3 Cichoń Functions

The Cichoń hierarchy of functions [2] (aka "length hierarchy") is a convenient way of measuring the length of controlled bad sequences. Given a monotone function $g: \mathbb{N} \to \mathbb{N}$, the Cichoń functions $(g_{\alpha})_{\alpha}$ are defined by transfinite induction by

 $g_0(x) = 0$, $g_{\alpha+1}(x) = 1 + g_\alpha(g(x))$, $g_\lambda(x) = g_{\lambda(x)}(x)$,

where $\lambda(x)$ denotes the x^{th} element of a fundamental sequence of ordinals converging towards the limit λ ; typically for $\lambda < \varepsilon_0$:

$$\lambda(x) = \begin{cases} \gamma + \omega^{\beta} \cdot (x+1) & \text{if } \lambda = \gamma + \omega^{\beta+1} ,\\ \gamma + \omega^{\lambda'(x)} & \text{if } \lambda = \gamma + \omega^{\lambda'} . \end{cases}$$

4.12.4 Maximal Order Types

This is the ordinal height of the maximal linearisation of a wqo, and was defined in [3].

4.12.5 Why Redux?

A somewhat similar principle relating the order type of termination orderings with the maximal length of derivations using the so-called slow-growing functions was sometimes called "Cichoń's Principle" after an observation in [1]. A related question appeared as Problem 23 of the *RTA List of Open Problems* and was solved in [4]; see http://www.cs.tau. ac.il/~nachum/rtaloop/problems/23.html.

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4.13 Weakly Computing Numerical Functions

Philippe Schnoebelen (ENS Cachan, FR)

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Open problem: What functions are weakly computable by VASS and extensions? **Background:** Hack 1976 [1] uses weak computing of multivariate polynomials with positive coefficients to show the undecidability of the equivalence problem. Mayr and Meyer 1981 [2] use weak computing of fast-growing F_n functions to show the Ackermann-hardness of the finite containment problem. Weak computing of the inverse F_n^{-1} functions by Reset Petri nets, i.e. VASS extended with reset operations, is instrumental in recent Ackermann-hardness results for monotone counter systems, see Schnoebelen 2010 [3].

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4.14 Critical Exponents of *k*-automatic Words and Generalizations

Jeffrey O. Shallit (University of Waterloo, CA)

- 1. Is there a decision procedure for determining the critical exponent (supremum over exponent of all factors) of a morphic word (i.e., the image, under a coding, of fixed point of an arbitrary morphism)?
- 2. Characterize the predicates for automatic sequences (e.g., squarefreeness) that are decidable in polynomial time. For example, Leroux has proved it for ultimate periodicity.
- 3. It is possible to prove that squarefreeness is not decidable, in general, for the obvious extension of automatic sequences to infinite alphabets (the k-regular sequences of Allouche and Shallit). But is it decidable for the special case of a fixed point of a morphism of the form i → (ai+b, ci+d) where a, b, c, d are integers? E. g., for (a, b, c, d) = (0, 0, 1, 1) we get the "ruler sequence" 01020103 · · · with critical exponent 2 and for (a, b, c, d) = (-1, 0, 1, 1) we get the Nørgård "infinity sequence" recently proved to have critical exponent 4/3.
- 4. Is $\sup\{x/y : (x, y)_k \in L\}$ computable for context-free languages L? Here by $(x, y)_k$ we mean the representation of the pair of integers (x, y) in base k.
- 5. Given a regular language $L \subseteq (\Sigma_k \times \Sigma_k)^*$ representing a set $S \subseteq \mathbb{N} \times \mathbb{N}$ of pairs of natural numbers, is it decidable if S contains a pair (p,q) with $p \mid q$?
- 6. Prove or disprove: if L is a regular language withquo_k(L) = Q^{≥0}, then L contains infinitely many distinct canonical representations for infinitely many distinct rational numbers. Here by "canonical" we mean "no leading [0,0]'s" and by quo_k(L) we mean {p/q : (p,q)_k ∈ L}.



Monday 31 March

09:00	Opening/Introduction	
09:30	Survey: Jérôme Leroux	Vector Addition System Toolbox
10:30	Coffee break	
11:00	Michael Blondin	Handling Infinitely Branching WSTS
11:30	Christoph Haase	Subclasses of Presburger Arithmetic and the Weak EXP
12:00	Petr Jančar	Equivalences of Deterministic Systems as Reachability
		Problems
12:15	Lunch and discussions	
15:30	Cake break	
16:00	Giorgio Delzanno	Infinite-State Model Checking with Data Recycling
16:30	Barbara König	Well-Structured Graph Transformation Systems
17:00	Break	
17:30	Parosh Aziz Abdulla	Cut-offs on Parameterized Systems
18:00	Dinner	

Tuesday 1 April

09:00	Survey: Sylvain Schmitz	Complexity Hierarchies Beyond Elementary
10:00	Philippe Schnoebelen	Ackermann-hardness for Monotone Counter Systems
10:30	Coffee break	
10:45	Ranko Lazić	Non-Elementary Complexities for Branching VASS, MELL, and Extensions
11:15	Richard Mayr	Deciding Coverability in Non-monotone Infinite-state Systems
11:45	Fernando Rosa-Velardo	Unordered Data Nets are as Hard as Lossy Channel Systems
12:15	Lunch and discussions	
15:30	Cake break	
16:00	Jeffrey Shallit	$Critical \ Exponents \ of \ k-automatic \ Words \ and \ Generalizations$
16:30	Igor Potapov	Reachability Problems for Braids, Knots, and Links – New Challenges for Computer Science
17:00	Break	
17:15	Mohammad Faouzi Atig	Timed Pushdown Automata
17:45	Diego Figueira	Reasoning About Data Repetitions with Counter Systems
18:00	Dinner	
Wednesday 2 April

09:00	Survey: Joel Ouaknine	Decision Problems for Discrete Linear Dynamical Systems: A Survey
10:00	Radu Iosif	Safety Problems are NP-complete for Flat Integer Pro- grams with Octagonal Loops
10:30	Coffee break	
10:45	James Worrell	Ultimate Positivity is Decidable for Simple Linear Recurrent Sequences
11:15	Bernard Boigelot	Symbolic Hybrid Transduction
11:45	Amir Ben-Amram	Linear Ranking Functions for Loops with a Precondition
12:15	Lunch and excursion	
18:00	Dinner	

Thursday 3 April

09:00	Survey: Wolfgang Thomas	Infinite Games and Reachability
10:00	Véronique Bruyère	Secure Equilibria in Weighted Games
10:30	Coffee break	
10:45	Laurent Doyen	Reachability in Partial-Observation Stochastic Games
11:15	Mikolaj Bojańczyk	Looping Over Infinite Structures
11:45	Slawomir Lasota	Turing Machines Over Infinite Alphabets
12:15	Lunch and discussions	
15:30	Cake break	
16:00	Igor Walukiewicz	Models of the lambdaY-calculus for Weak Monadic Second- Order Logic
16:30	Olivier Bournez	On the Hardness of Solving Ordinary Differential Equa- tions
16:45	Break	
17:15	Jean Goubault-Larrecq	The VJGL Lemma
17:45	Tomas Brazdil	Zero-Reachability in Probabilistic Multi-Counter Auto- mata
18:00	Dinner	

Friday 4 April

09:00	Peter Habermehl	Temporal Logics and Automata on Multi-attributed Data
		Words with Ordered Navigation
09:30	Antonín Kučera	Adversarial Patrolling Games
10:00	Stefan Kiefer	Analysis of Probabilistic Parallel Processes
10:30	Coffee break	
11:00	Andreas Podelski	Software Model Checking via Petri Net Language Inclu-
		sion

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Richard Mayr



Report from Dagstuhl Seminar 14142

Spatial reference in the Semantic Web and in Robotics

Edited by

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— Abstract –

The seminar on "Spatial reference in the Semantic Web and in Robotics" was held from March 30 until April 4, 2014. Seminar participants presented their work related to spatial reference from the viewpoint of Robotics, Spatial Cognition, Geospatial information and the Semantic Web. Groups worked on concrete questions and challenges which were developed during the seminar, some of which resulted in follow up work. This report summarizes the outcomes of the seminar discussions and presents the abstracts of participant talks.

Seminar March 30 to April 4, 2014 – http://www.dagstuhl.de/14142

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1 Executive Summary

Aldo Gangemi Verena V. Hafner Werner Kuhn Simon Scheider Luc Steels

Motivation

Places ("downtown"), spatial objects ("highway 1") and localized events ("hurricane Katrina"), are commonly referred to in the Semantic Web. They serve to search for and link to information across domains. Spatial reference systems, such as WGS84¹, allow for representing

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Spatial reference in the Semantic Web and in Robotics, *Dagstuhl Reports*, Vol. 4, Issue 3, pp. 181–201 Editors: Aldo Gangemi, Verena V. Hafner, Werner Kuhn, Simon Scheider, and Luc Steels

¹ The world geodetic system https://en.wikipedia.org/wiki/World_Geodetic_System, a standard reference ellipsoid and coordinate frame for encoding locations on the earth surface.

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such references as points or regions. This makes them amenable not only for mapping, but also for powerful location-based querying, navigation support and computing.

Spatial references are also fundamental in embodied cognition and robotics. Egocentric and allocentric spatial reference frames underlie robot learning and interaction. Decades of research in cognitive robotics highlight the role of social interaction, joint attention, language games, and visual discrimination games in establishing referents for symbols. The most well-known experiment is that of the Talking Heads. Spatial relations, such as right, front, left, behind, serve to name and identify other objects in a self-organizing vocabulary. Affordance-based cognition is a source of spatial reference in robots as well as in humans. However, so far, this research is only loosely connected to information science and the Semantic Web.

Existing options to localize information in the Semantic Web and in Robotics through coordinate systems cover only limited cases of spatial reference. Humans localize referents in space in many ways, based on different tasks and spatial competencies. For example, the location of a workplace may be linked to people, tasks, and infrastructures. It can be specified in terms of a coordinate system or, alternatively, in terms of containment, connectedness and accessibility in a building; yet another option is to specify it by the possibility to perform certain activities, such as sitting or reading and writing at the workplace.

The seminar

This Dagstuhl Seminar brought together leading international researchers from the Semantic Web, Spatial Cognition, Geo-informatics and Cognitive Robotics to work on the application, synthesis, formal construction, extension, and use of spatial reference systems, identifying challenges and research opportunities. The seminar gathered 27 researchers, 9 from Spatial Cognition and reasoning, 6 from Geo-informatics, 7 from Cognitive Robotics, and 5 from the Semantic Web.

Seminar participants identified a number of concrete links between these communities that are being exploited for future research and development. For example, spatial reference systems of robots and corresponding cognitive spatial concepts can be used in order to describe resources accessible in the world, and Semantic Web technology to publish those descriptions for information access. Locations can be described in ways which are more closely related to humans, based on qualitative relations and environmental referents, and for environments which are difficult to localize by a GPS. In this way, it becomes possible to share location descriptions among humans and robots and thus to localize resources of interest (e. g. rooms, people, places) published in the Web of data. Vice versa, spatial referents and descriptions in the Semantic Web may guide robots towards accessible things in the world. Robots may function as embodied surrogates of human observers exchanging information on the Web of Data encoded in terms of their own reference systems.

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3 Overview of Talks

3.1 Spatial Descriptions in Formal and Natural Languages

Brandon Bennett (University of Leeds, GB)

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This paper explores the complex mapping between language and meaning and the repercussions this has for formalising natural language semantics. The general problem will be investigated by consideration of the domain of spatial descriptions, especially those that describe a spatial relationship between two entities. I argue that the meanings of spatial expressions of natural language can be modelled in terms of a cluster of distinct formal definitions, each of which corresponds to an artificially precise version of the informal natural concept. Moreover, I show how one can derive a probability distribution over possible formal interpretations of natural language vocabulary and phrases by analysing their occurrence in a corpus that is representative of typical language use.

3.2 Visuo-Spatial Reasoning for Computational Cognitive Systems

Mehul Bhatt (Universität Bremen, DE)

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We pursue visuo-spatial representation and reasoning from the viewpoint of the research areas of artificial intelligence, commonsense reasoning, and spatial cognition and computation.

We propose **declarative spatial reasoning** as the ability to (declaratively) specify and solve real-world problems related to geometric and qualitative visuo- spatial representation and reasoning [2]. The problems that we address in this context encompass both specialist and everyday instances identifiable in a range of *cognitive technologies* and *spatial assistance systems* where spatio-linguistic conceptualisation & background knowledge focussed visuospatial cognition and computation are central [3].

As a first step toward the systematic development of the declarative spatial reasoning method, we have initiated formalisations of *space* and *spatial reasoning* within constraint logic programming [2, 6, 7]. We have developed CLP(QS), a declarative spatial reasoning system capable of modelling and reasoning about qualitative spatial relations pertaining to multiple spatial domains, i.e., one or more aspects of space such as topology, and intrinsic and extrinsic orientation, size, distance etc. With CLP(QS), users and application developers may freely mix object domains (i. e., points, line-segments, and regions) with the available spatial domains. CLP(QS) also offers mixed geometric- qualitative spatial reasoning capabilities, and in its current form, basic quantification support offering the means to go back from qualitative relations to the domain of precise quantitative information.

The emphasis in CLP(QS) is on the seamless integration of declarative visuo- spatial (computational) problem-solving capabilities within large-scale hybrid AI systems, and cognitive (interaction) technologies. Currently, integration is achieved via the medium of *logic programming* – specifications in the form of (domain) *facts* and *rules* consisting of mix of, for instance, background semantic or conceptual knowledge, spatio-temporal knowledge, and knowledge about action and dynamics. The general concept of declarative spatial reasoning

lends itself to re-interpretations and extensions with other perspectives such as diagrammatic representations.

CLP(QS) marks a clear departure from other (relational-algebraically based) spatial reasoning methods / tools by its use of the constraint logic programming framework for formalising the semantics of mixed geometric and qualitative spatial representation and reasoning. The approach has demonstrated applicability in several domains, most recent examples being architectural design cognition [5], cognitive vision [4], geospatial information systems [1].

The CLP(QS) system is also being designed and used as a pedagogical tool to be used as part of university based courses at the interface of Artificial Intelligence, Knowledge Representation and Reasoning, Cognitive Systems, and Spatial Informatics.

CLP(QS): A Declarative Spatial Reasoning System. http://www.spatial-reasoning.com

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3.3 Gestures in Human-Robot Interaction

Saša Bodiroža (Humboldt-Universität zu Berlin, DE)

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Saša Bodiroža

Joint work of Bodiroža, Saša; Hafner, Verena V.; Lara, Bruno; Doisy, Guillaume; Jevtić, Aleksandar

Intuitive human-robot interaction relies on multimodal communication between humans and robots by means of symbols which are easily understood by participants. This work focuses on the use of gestures in human-robot interaction and consists of two steps: development of gesture vocabularies and gesture recognition.

Gesture vocabularies represent mappings between actions and gestures. Usually, they are constructed by system designers and represent 1–1 mappings. This is far from the case in the real world, where these are n–n mappings. Therefore, they need to be defined through observation of the associations people make between particular actions and gestures. To construct a human gesture vocabulary, a user survey is performed to collect gestures which people usually associate with pre- selected actions [1]. The results present an important input before the design stage of the gesture recognizer. A robot gesture vocabulary is developed in a similar manner, where participants are asked to rank videos of pre-recorded robot gestures, which are based on the gestures that humans perform. Resulting gestures might not be the best for a particular person. In order to make them more general, interactive evolution of these gestures is performed to come up with better variant of these gestures. Every time a human being gesture, they tend to to perform the same gesture with slight variances in direction, size, velocity, starting and ending positions of the stroke, location where they gesture and the orientation between the person who gestures and the observer.

One way to make gesture recognition invariant to these variables is to pre-process trajectories, before the recognition, so that these features are removed. A gesture recognition algorithm, based on dynamic time warping, presents a way to recognize gestures which are performed with varying velocity [2]. Inputs are gesture trajectories, which are obtained using a RGB-D camera and transformed from the robot's frame of reference to that of the person. Furthermore, the trajectories are normalized and aligned with the trained gestures to make the recognizer robust to gestural size and location. Finally, the gesture recognition is made more robust to by including an invariance to the direction of the gesture. Both algorithms are trained using one sample per gestural class. This leads to unrestricted gesture recognition, enabling its application in real world scenarios. However, the above mentioned features (e. g. direction and size) are relevant for the understanding of some gestures and a disambiguation framework is presented, which is trained to disambiguate gestures based on the output of the recognizer and these features where they are relevant.

Work on motion control learning will be presented through two experiments. Both present action execution systems that rely on learned sensorimotor schemes. These schemes are learned as a product of the interaction of an agent with its environment. In the first experiment, a mobile agent learns an association between changes in its sensory perception and the random movements it performs (so called motor babbling) [3]. Once it has this acquired knowledge, the agent is then capable of performing a mirror action to match an observed gesture. This is seen as a first step toward learning motor control strategies for a robot control task. In the second experiment, it learns associations between changes in its sensory perception and its movement, guided by the demonstrator. After learning, it is capable of executing the necessary motor commands to go to a location where the demonstrator is pointing.

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3.4 Why Spatial Reference should eschew projections

Nicholas Chrisman (RMIT University – Melbourne, AU)

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A large proportion of GIS databases use a local reference system based on linear measurements (metres) on a projection plane of some form. This practice creates systematic errors which are not corrected in routine practice.

Projection error is nothing new, but it is no longer required as computation has become cheaper. It is time to stop this practice and move to the round (ellipsoidal) Earth as a reference system. Current dynamic reference frameworks (such as ITRF) provide a more solid and sustainable basis for spatial reference.

3.5 "The kids are in the kitchen!!" Artificial spaces as place-reference systems

Helen Couclelis (University of California – Santa Barbara, US)

Emergency personnel entering a house they have never seen before will turn towards the living room or dining area rather than the bedrooms in order to reach the kitchen and rescue the children. This is a simple inference to make because a house, like all artificial things, is made for a purpose: here, the purpose of supporting a household's everyday activities, and more specifically in the case of the kitchen, the activity of storing and preparing food, which is closely linked to the activity of eating (but not of sleeping). The same general principle applies to artificial or artificially configured spaces at any scale, from that of the layout of the kitchen itself to those of farms or harbors or national parks, in that each of these spaces must function so as to enable the activities and artificial spatial structures can be modeled with a degree of accuracy sufficient for many applications, allowing inferences of structure from activity and conversely. In geographic-scale artificial spaces that same logic connecting functional relations and spatial structure conveys properties of place- reference systems. Indeed, by designating a place with a name that reflects its purpose (the kitchen, the auditorium, the barn, and so on), one provides valuable information on the likely location of other places functionally related to the former.

3.6 An Analysis of the Semantics of Spatial Representation and Relations

Anne Cregan (Intersect – Sydney, AU)

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I'd like to present my analysis of the semantics of spatial representation and relations through a number of examples. These will highlight the importance of asking these questions and being able to formulate good answers for them:

- 1. What is the frame of reference, i.e., the space to be represented? What are its underlying dimensions and properties?
- 2. What is our motivation for representing this space, i. e., what are we actually trying to do? What kind of representation is most appropriate for this?
- 3. How do we intend to "ground" the representation to the space, i.e. how should we establish correspondence points, lines or other features which connect the representation to the space being represented?
- 4. When is a space really a network?
- 5. What is the difference between an absolute and relative reference to a location within a space?
- 6. What spatial relations are meaningful in the space and how should we represent them?
- 7. Factors pertaining to agents and objects operating in the space
- 8. Factors pertaining to solving problems of logistics, optimisation etc. as they relate to the space

As this analysis works through what I believe are some of the most fundamental issues and lays out a framework for further discussions, it would best be placed early in the schedule.

3.7 A preliminary sketch of some definitions for "Data", "Information", "Knowledge" and "Wisdom"

Anne Cregan (Intersect – Sydney, AU)

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Stimulated by discussion during the seminar, this is a preliminary sketch of how one might define these terms.

Some of the questions raised are:

- Are these terms representing the categories that are discrete or do they fall on a spectrum?
- If they are values falling on a single dimension, then what is the underlying dimension?
- Is wisdom on an orthogonal dimension to the data-to-knowledge spectrum?

3.8 Spatial Frames across Language and the Web

Aldo Gangemi (CNR - Rome, IT)

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My presentation is an introduction to frames and knowledge patterns, as they can be applied – jointly with semantic web, linked data, and knowledge extraction techniques – to empirical investigations of Spatial Knowledge Representation (SKR).

Frames are task-oriented invariants in conceptualizing the world. They are related to both cognition (conceptual schemas) and problem solving (design patterns). Frames appear in data, ontologies, conceptual schemas, language, web and interaction formats, etc. A structureneutral, broad notion of frames is "Knowledge Pattern" (KP), a notion introduced firstly by Robert de Beaugrande in the seventies to generalize over frames, scripts, schemas, as they were used in AI, linguistics, and cognitive science. Knowledge patterns have been formalized firstly by Peter Clark in late nineties, and applied to the semantic web by Aldo Gangemi and Valentina Presutti. In this late notion, knowledge patterns are meant for reusability and good design practices: they are reusable successful solutions to recurrent modeling problems. A useful feature of KPs is that they are invariant across several representation layers (e. g. natural language-data-schema; schema-data, etc.): therefore KPs are supposed to enable interoperability and knowledge discovery across arbitrary representation languages and formats. Knowledge patterns emerge as top-down collections of good practices, or as empirical findings from data, text, ontologies, etc.

SKR is core to any linked data design project. Currently all important LOD bubbles contain spatial knowledge: DBpedia (about 800 thousand spatial entities and about 3 million spatial facts), Yago (about 900 thousand spatial entities), Geonames, GeoLinkedData. Schemas have been designed by reusing existing SKR, notably the GeoSPARQL ontology, which incorporates part of the RCC8 spatial algebra. On one hand, linked spatial data are however incomplete and prone to inconsistencies, e. g. 3646 Yago spatial entities are typed so that inconsistencies emerge as soon as plausible disjointness axioms are used to reason over that ontology. On the other hand, the Web is an ideal platform for experimenting with SKR. Besides the amount of public data and their public, reusable identities, the Web manifests original and interesting SKR problems: user-centric space, web-specific space, spatial predicates embedding events or other relations.

When natural language is put into the picture, things become even more exciting: Levinson's Spatial Reference Systems (SRS: Absolute, Intrinsic, Relative) map in a complex way against linguistic constructions: locally constructed SRS, metonymic SRS, metaphoric SRS. Levinson's SRS and SRS emerging from the Web and from particular linguistic constructions correspond to novel Spatial Knowledge Patterns (SKP). Some of them can be found in top-down KP repositories such as FrameNet, others can be discovered from data and text. Others are found or emerge out of text. Deep machine reading such as the one performed by the FRED tool (http://wit.istc.cnr.it/stlab-tools/fred) allows to combine knowledge extraction based on NLP algorithms with existing linked data, so enabling a human-like contextual reading of text including spatial references.

In order to apply SKP to SRS, we need powerful KPs that abstract from the high variability of SRS phenomena. A good candidate for reuse is the Descriptions and Situations (D&S) pattern, which is able to pair "duper" relations, typically a factual one (e.g. a situation with entities at places during events with characteristics), and a descriptive one (e.g. a

description of a relative SRS used to understand that situation). Applying D&S to SKR on the Web requires reification of n-ary relations, "punning" of predicates, and dynamic typing of named graphs for RDF serialization. The SRS pattern drafted during the seminar is a case of SKP, and is partly inspired by D&S.

Please refer to the slides of my presentation at the seminar for details.

3.9 Cross-World Identity in Conceptual Spaces

Giancarlo Guizzardi (UFES – Vitoria, BR)

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Main reference G. Guizzardi, "Logical, Ontological and Cognitive Aspects of Objects Types and Cross-World Identity with applications to the theory of Conceptual Spaces," to appear in P. Gardenfors, F. Zenker, eds., "Applications of Geometric Knowledge Representation," Synthese Library, Dordrecht, Springer; forthcoming.

The theory of Conceptual Spaces put forth by the Swedish philosopher and cognitive scientist Peter Gärdenfors proposes a geometrical model for representing and reasoning with Categories and Properties. The theory has been shown to serve as a valuable tool in philosophy, cognitive science, linguistics and computer science, in a number of applications ranging from foundations for conceptual modeling to Robotics. However, recently, the theory has suffered criticisms due to its insufficiency in supporting the structure of judgments and, in particular, its unsatisfactory treatment of cross-world identity and persistence for enduring individuals. In this work, I briefly discuss a philosophically and cognitively well-founded theory of object categories as well as a system of Sortal Intensional Logic (a Modal Logic with Individual Concepts and Sortal-restricted quantification) derived from this theory. Moreover, I illustrate how these results can be used to address the aforementioned limitations of the theory of Conceptual Spaces.

3.10 Attention Models in Robotics

Verena V. Hafner (Humboldt-Universität zu Berlin, DE)

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 Joint work of Hafner, Verena V.; Schillaci, Guido; Bodiroža, Saša
 Main reference G. Schillaci, S. Bodiroža, V. V. Hafner, "Evaluating the Effect of Saliency Detection and Attention Manipulation in Human-Robot Interaction," International Journal of Social Robotics, 5(1):139–152, 2013; available open access.

URL http://dx.doi.org/10.1007/s12369-012-0174-7

The ability to share the attention with another individual is essential for having intuitive interaction and to communicate about spatial events. Two relatively simple, but important prerequisites for this, saliency detection and attention manipulation by the robot, are identified. By creating a saliency based attentional model combined with a robot ego-sphere [2] and by adopting attention manipulation skills, the robot can engage in an interaction with a human and start an interaction game including objects as a first step towards a joint attention [1].

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3.11 Ontology Design Patterns for Ocean Science Data Discovery

Pascal Hitzler (Wright State University – Dayton, US)

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Joint work of Hitzler, Pascal; Krisnadhi, Adila; Arko, Robert; Carbotte, Suzanne; Chandler, Cynthia; Cheatham, Michelle; Finin, Timothy; Janowicz, Krzysztof; Narock, Thomas; Raymond, Lisa; Shepherd, Adam; Wiebe, Peter

EarthCube is a major effort of the National Science Foundation to establish a next-generation knowledge architecture for the broader geosciences. Data storage, retrieval, access, and reuse are central parts of this new effort. Currently, EarthCube is organized around several building blocks and research coordination networks. The NSF EarthCube OceanLink project is currently under way to integrate the two major U.S. ocean science repositories, BCO-DMO and R2R, using a flexible approach based on ontology design patterns, which is set to scale to significant breadth and depth. Ontology design patterns are the method of choice for this integration.

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3.12 Spatial Referencing

Werner Kuhn (University of California – Santa Barbara, US)

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I gave a very brief introduction to the basic ideas underlying spatial referencing on the earth. My framing of the topic suggested ways to generalize from geographic to other spaces and from space (and time) to measurements in general.

3.13 Spatial Cognition in Robotics

Bruno Lara Guzman (Universidad Autónoma del Estado de Morelos, MX)

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Intelligence and thinking are mental phenomena essentially linked to both our bodies and the environmental conditions in which we are immersed.

We understand the physical world according to our own experience. The faculties, capabilities and skills to dynamically interact with the world, which as adult humans we posses, emerge through a long process of tuning and rehearsing of sensori-motor schemes.

A very important example is the acquisition of the sensori-motor schemes that code for the capabilities and reaches of our body. This set of schemes provide us with many cognitive tools, among them the knowledge and coding of our body map, essential for among other tasks navigating around the environment.

Throughout its short history, artificial intelligence research has witnessed at least one major paradigm shift, namely from a cognitivist perspective, which conceived cognition as a amodal symbol crunching activity to a new perspective emphasizing the role of the body and environmental structures in cognition.

In the last decades, together with the rest of the sciences studying cognition the shift in paradigm has been towards the rediscovery of the importance the body of agents has on the development of cognition.

In what has become known as embodied cognition, it is widely accepted now that, to be able to understand and replicate intelligence, it is necessary to study agents in their relation to their environment [1]. The subjects of study should be agents with a body, that learn through interaction with their environment and that this learning should be a developmental process.

Pursuing the same aims, cognitive robotics takes its inspiration from studies of cognitive development in humans. Artificial agents or robots, by having a body and being situated in the real world, assure a continuous and real-time coupling of body, control and environment.

Theories of grounded cognition have also had a great impact on this quest. In general, these theories reject the use of modal symbols for the representation of knowledge, focusing on the role of the body for its acquisition [5]. More importantly for our purposes, grounded cognition focuses on the role of internal simulations of the sensorimotor interaction of agents with their environment.

For the advocates of grounded cognition modal simulations, such as recreations of perceptual, motor and introspective states, are important components that allow the development of high cognitive abilities. Such recreations could account for the off-line characteristics of cognition, in which internal simulations of sensory-motor cycles are executed.

Studies that account for these theories provide experimental results that support the importance of internal models and multimodal representations to form the ground capable of supporting the whole cognition scaffolding.

In the quest of a basic internal simulation mechanism forward and inverse models have been proposed [3]. A forward model is an internal model which incorporates knowledge about sensory changes produced by self-generated actions of an agent. Given a sensory situation S_t and a motor command M_t (intended or actual action) the forward model predicts the next sensory situation S_{t+1} . While forward models (or predictors) present the causal relation between actions and their consequences, inverse models (or controllers) perform the opposite transformation providing a system with the necessary motor command (M_t) to go from a current sensory situation (S_t) to a desired one (S_{t+1}) . 193

Forward and inverse models become central players in cognition, as they naturally fuse together different sensory modalities as well as motor information providing agents with multimodal representations [2].

We believe that the joint and coordinate action of both forward and inverse models gives an agent a practical sense of situations and can even account for subjective experience as a ground for consciousness [4].

In this new perspective internal models have become a keypoint, given the capabilities they allot agents. We believe that these type of models, specially internal and forward models, have not been fully studied and their usefulness not properly exploited. We present a short review of some of the most well-known architectures and implementations in the area in the search to identify and try fill some of the gaps in their study.

In our research we use these models to let agents learn the spatial characteristics of their own bodies, the environment around them and the sensorimotor associations arising from the interaction among these two.

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3.14 Observation of Human Activity in Intelligent Space – Human-Object/Environment Interaction

Mihoko Niitsuma (Chuo University, JP)

Main reference M. Niitsuma, K. Yokoi, H. Hashimoto, "Describing Human-Object Interaction in Intelligent Space," in Proc. of the 2nd Int'l Conf. on Human System Interaction (HSI'09), pp. 392–396, IEEE, 2009. URL http://dl.acm.org/citation.cfm?id=1689359.1689428

This talk presents an observation system of human-object interaction in the Intelligent Space (iSpace). Object information is necessary to describe events and human activities which happen in environments. Especially, names, colors, size and shapes of objects can be described manually because we can consider that the information will not change. On the other hand, information such as locations of objects, frequency of use of the objects, the users and motion patterns while using the objects can not be described manually because they depend on individuals and contexts when the objects are used. Therefore, we decided to obtain these kinds of object information through observation of human-object interaction.

3.15 Representing structural, functional and organizational dimensions of indoor spaces

Kai-Florian Richter (Universität Zürich, CH)

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 Joint work of Richter, Kai-Florian; Winter, Stephan; Satosa, Sigit
 Main reference K.-F. Richter, S. Winter, S. Santosa, "Hierarchical Representations of Indoor Spaces," Environment and Planning B: Planning and Design, 38(6):1052–1070, 2011.
 URL http://dx.doi.org/10.1068/b37057

People's mental organization of their spatial knowledge is (often) hierarchical. For example, place descriptions have been shown to have hierarchical structure. Such hierarchical structures provide efficient means to if needed refine descriptions (e.g., to disambiguate) or to coarsen them (e.g., if unsure about the details). Also, different (groups of) people have different views (conceptualizations) of a space, for example, a building, that is reflected in differences in their mental representation and the way they talk about that space.

We developed a hierarchical representation of indoor spaces that is based on image schemata and captures structural, functional and organizational dimensions of a space. The representation allows accounting for different use roles (user groups).Still, there is further research required , for example, to automatically convert floor plans or to properly link geometry with the representation.

3.16 Decontextualizing spatial words in the process of language acquisition

Katharina J. Rohlfing (Universität Bielefeld, DE)

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For establishing a representation from (1) a scene on the one hand and (2) a spatial preposition describing this scene on the other hand, different memory processes seem to be responsible. While a first exposure to a new preposition is "fast mapped" in which process contextual cues are crucial, children need to be exposed to different situations in order to "slow map" the new word. In this latter process, the learner becomes able to apply the acquired word in situations that are unfamiliar and provide little cues.

3.17 Grounding Spatial Language in Sensorimotor Experience

Yulia Sandamirskaya (Ruhr-Universität Bochum, DE)

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Vulia Sandamirskaya

Dynamic Field Theory (DFT) is a mathematical and conceptual framework, in which emergence of cognitive processes from continuous in time and in space neuronal dynamics may be modelled. Elementary cognitive functions, such as memory formation, feature binding, decision making, and coordinate frame transformations may be expressed in this framework using Dynamic Neural Fields, organised in autonomous neural-dynamic architectures. In

my talk, I demonstrate how the principles, structures, and dynamics of DFT may be put together in an architecture, capable of grounding spatial language in a visually perceived scene, answering queries about the scene, and directing actions at objects in the scene by spatially referencing them.

3.18 Treasure maps. Spatial reference systems for the common man

Simon Scheider (Universität Münster, DE)

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Spatial reference systems are not only a basis for producing maps, they are also a powerful tool for localizing objects in everyday human communication. The human localization practice, as applied in orientation tasks, is very different from the practice underlying geographic coordinate systems, as used in current IT systems or in GPS. While geographic coordinates are grounded in the earth as referent, human localization practice resembles a "treasure map", i.e., a description of locations relative to various kinds of referent objects and spatial operations. One way to analyze such systems is to look at localization games, such as "orienteering". The international orienteering federation proposes a standard syntax for describing the locations of control flags in an orienteering terrain. This standard uses a well defined range of definite descriptors, types and qualities for selecting reference objects (relatums) in the landscape, as well as a choice of relations to determine locations relative to objects, based on cardinal and vertical directions, imposed orderings and object morphology. The benefit of such reference systems is that they work indoors as well as outdoors, at least in principle, and that they reflect human localization practice. In future work, one could investigate how to formalize orienteering systems, and how to support spatial computations as well as translations to geographic coordinate reference systems. A concrete challenge is to build a digital orienteering system, which helps players compare and retrieve control descriptions, and users describe locations precisely, in a manner which comes close to their habit. From a larger perspective, such a system could demonstrate how to make available spatial reference systems for the common man in the Semantic Web, in order to describe locations of arbitrary resources.

3.19 Place-based GIS

Stephan Winter (The University of Melbourne, AU)

People reason about space by places, and configurations of places. Configurations of known (or more salient) places form the spatial reference system in language: An expression "the coffee shop opposite the library" assumes the library (relatum) is shared spatial knowledge, and positions the unknown or ambiguous coffee shop (locatum) to this relatum.

Language typically remains qualitative, i.e., collecting corpora of natural language descriptions would provide arbitrary large sets of triples <locatum, reference, relatum> (for binary spatial relationships). These triplets do not only provide a relationship, they also distinguish a feature that is positioned from a feature that allows positioning. The set

of relata must be the features commonly known, or at least shared between speaker and recipient in the individual communication situations. In this sense, the set of relata seems to determine a spatial reference frame.

This talk poses the challenge to build place-based GIS: GIS where the frame of reference comes from configurations of known places, instead of a metric externally defined spatial reference system.

3.20 Qualitative Relations vs. Locative Expressions

Diedrich Wolter (Universität Bamberg, DE)

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 Joint work of Mast, Vivien; Wolter, Diedrich
 Main reference V. Mast, D. Wolter, "Context and Vagueness in REG," in Proc. of the 2013 Workshop on Production of Referring: Bridging the gap between cognitive and computational approaches to reference (PRE-CogSci'13), 6 pages, 2013.

 URL http://pre2013.uvt.nl/pdf/mast-wolter.pdf

Qualitative spatial reasoning is a subfield of AI research involved with symbolic representations that aims to capture common sense spatial concepts. Representations in qualitative spatial reasoning are based on finite sets of relations that categorize spatial properties by comparison. Among other applications, qualitative spatial representations are widely acknowledged to provide a basis for natural language semantics as well relations need to exhibit specific features to make reasoning efficient. However, we recently observed properties of locative expressions that do not align with qualitative representations studied so far. This talk will contrast some of the computational requirements with language use.

4 Working Groups

4.1 Spatial reference design pattern

Aldo Gangemi, Pascal Hitzler, and Simon Scheider

During the seminar, one group worked on an ontology design pattern which captures central aspects of Stephen Levinson's typology of reference frames (relative, absolute and intrinsic) and makes them formally explicit, so that one can distinguish the different ways how humans and robots refer to space. The idea is to design an ontology pattern which can be used to encode the different ways how agents actually construct spatial referents. Examples for the latter are: walk for 30 minutes and you're there; in front of the house; outside the house; north of the oak tree in the park; this theater, room 2, seat 4A; the parking lot next to the cinema; between the tree and the well; at the foot of the cliff; the tree uphill from the house. In robotics, spatial referents of this kind play a major role not only in sensory-motor coordination, but also in robot interaction and learning. Can we generate a general design pattern that allows to document how agents construct spatial referents? This would enable automatic descriptions of locations visited by a robot or a human, which could be published and compared in the Semantic Web as a communication layer. The group plans to write a paper about this, in which concrete spatial reference frames used in robotic experiments are taken as empirical data on which the pattern is tested.

4.2 Draft OWL specification of Spatial Reference Pattern

Aldo Gangemi, Pascal Hitzler, and Simon Scheider

License ⊕ Creative Commons BY 3.0 Unported license © Aldo Gangemi, Pascal Hitzler, and Simon Scheider URL http://www.ontologydesignpatterns.org/cp/owl/spatial-reference.owl

This is a draft of the OWL spec for the Spatial Reference Pattern, as designed in Dagstuhl by Aldo Gangemi, Pascal Hitzler, and Simon Scheider. It is still very incomplete in terms of axioms, domain coverage, and annotations. No links are yet provided to existing vocabularies.

4.3 InnoCentive Challenge Submission on Gazetteers for Place Descriptions

Werner Kuhn (University of California – Santa Barbara, US)

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We propose an annual computational cognition competition to build gazetteer services that interpret geographic place descriptions. Examples for such descriptions are "the hill along Grattan street" or "in front of the door of the smithy in Port Khazard". Locating unnamed places is increasingly important and helps to interpret and integrate big data, in applications ranging from the digital humanities through physical infrastructure maintenance to security. Solutions shall map described places from a corpus as points, lines, or polygons at an adequate scale, using an online map service; they shall also return the geometries encoded as well-known text , at a resolution corresponding to their estimated precision.

5 Panel Discussions

5.1 The discussions

A number of concrete questions evolved during the seminar and were investigated in group work. During the afternoon sessions, participants split into groups discussing the following topics:

- How to construct a digital orienteering system? Such a system may help people who plan orienteering games² generate and share orienteering descriptions for a given terrain, generate automatic cartographic mappings from orienteering descriptions, or it may help robots play this game.
- What are criteria for selecting spatial referents? There seems to be a trade-off between a need for generalization and retainment of the benefits of particulars. This is closely related to the problem of selecting landmarks.
- How do spatial reference descriptions depend on a task? Humans possess a repertoire of spatial reference systems. Furthermore, ad-hoc reference systems can be built. The question is whether it is possible to define a given task in a way such that we can decide

² http://en.wikipedia.org/wiki/Orienteering

which reference system should be selected from the repertoire or generated ad-hoc, in a manner that it is optimally suited to the goal. Also, accessibility to reference systems needs to be considered, that is: what reference systems are available to the audience? Goal and accessibility might be conflicting, e.g. the goal might be to give the most definite location, however the audience might not know these terms.

- Which action hierarchies need to be considered on different levels of detail and how do these determine spatial descriptions? An example would be the linkage between an event in time (e.g. "breakfast") and a place where it happens (e.g. "downstairs"), and how a hierarchy is affected when a change occurs in terms of actions or goals.
- How can maps be reconstructed from narratives? For example: "There were 8 people sitting around the table, six with laptops in front of them and two with coffee." The challenge is that it is possible to reconstruct multiple depictions from a single narrative such as the one above.
- Is there an ontology design pattern for spatial reference, along the ideas of S. C. Levinson? It would need to include a minimal set of spatial concepts (axis, relations) which are needed in order to describe relative, absolute and intrinsic reference systems. It would allow us to describe and publish robot experiments as well as human referencing on the Web.
- How can spatial reasoning be brought into the Semantic Web? Which reasoners, formalisms and spatial relations should be supported, and how can existing systems be integrated? Technically, SPARQL basic graph patterns and filters can be hacked in order to support existing spatial reasoners.
- How could we develop a computational model for answering "where" questions? An example of a "where" question is "Where is downstairs?" The question implies that communicating agents know what is meant with downstairs. The discussion led to the use-case of navigation instructions across different modes of transportation and different spaces, where the transportation modes might be driving, walking, cycling. Different modes of communication of the instructions should be considered (e.g. verbal, tactile and visual).

5.2 The outcomes

As a concrete outcome of the seminar, participants agreed to follow up on a number of promising interdisciplinary research topics. The latter include tasks such as paper writing, software development and formulations of technical challenges (with people in brackets being responsible for coordination):

- 1. Write a paper on a spatial reference design pattern. Automatic publication of descriptions of locations visited by a robot, using the Semantic Web as a sharing platform (Simon Scheider)
- 2. Offer qualitative spatial reasoning (e.g. RCC8++), as implemented in SparQ³, via a SPARQL engine (by result enrichment) based on the GeoSPARQL vocabulary⁴. Implement a software package (endpoint) which integrates spatial reasoners and could be

³ http://www.sfbtr8.uni-bremen.de/project/r3/sparq/

⁴ http://www.opengeospatial.org/standards/geosparql

used with other reasoners, too. This idea already produced some results.⁵ (Thomas Scharrenbach)

- 3. Organize a hackathon on integrating spatial reasoning into the Semantic Web. (Brandon Bennett)
- 4. Write a paper on grounding the Semantic Web. How do we propose to ground spatial terms in the Semantic Web? How do Luc's ideas, spatial science, cognitive science and the Semantic Web fit together? How to take into account the communication situation and the purpose of information? (Anne Cregan)
- 5. Formulate a which and where question challenge: How to determine which reference frame is suitable for a certain where task, based on purpose and action? (Stephan Winter)
- 6. Formulate a challenge for a Turing test for localization. Test whether robots and humans perform equivalently on localization tasks and locative description tasks (Diedrich Wolter)
- 7. Formulate a challenge for building a gazetteer which interprets place descriptions. Examples for such descriptions are "the hill along Grattan street" or "in front of the door of the smithy in Port Khazard". Submitted as an InnoCentive challenge. (Werner Kuhn)

⁵ https://qsr4sw.wordpress.com/

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