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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 13271

Theory of Evolutionary Algorithms

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Abstract

This report documents the talks and discussions of Dagstuhl Seminar 13271 "Theory of Evolutionary Algorithms". This seminar, now in its 7th edition, is the main meeting point of the highly active theory of randomized search heuristics subcommunities in Australia, Asia, North America and Europe. Topics intensively discussed include a complexity theory for randomized search heuristics, evolutionary computation in noisy settings, the drift analysis technique, and parallel evolutionary computation.

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1 Executive Summary

Benjamin Doerr
Nikolaus Hansen
Jonathan L. Shapiro
L. Darrell Whitley

Evolutionary algorithms (EAs) are stochastic optimization methods that are based on principles derived from natural evolution. Mutation, recombination, and selection are iterated with the goal of driving a population of candidate solutions toward better and better regions of the search space.

In recent years, new methods have been developed at a rapid pace. Some of the advancements for continuous optimization methods have been enabled by focusing on how evolutionary algorithms can be compared and contrasted to more traditional gradient based methods. Arguably, evolutionary algorithms are one of the best methods now available for derivative-free optimization (DFO) on higher dimensional problems.

Another area of rapid recent advancement is in the area of run-time analysis for evolutionary algorithms applied to discrete optimization problems. Here, some techniques could be

successfully borrowed from traditional algorithm analysis, but many new techniques were necessary to understand the more complicated stochastic processes arising from nature-inspired algorithms.

EA theory has gained much momentum over the last few years and has made numerous valuable contributions to the field of evolutionary computation. Much of this momentum is due to the Dagstuhl seminars on "Theory of Evolutionary Algorithms", which has become the leading meeting for EA theorists in the world.

Specific Topics

This year, the following topics had the particular attention of organizers, speakers both of overview and specialized talks, and participants of the breakout sessions (also called "working parties" or "working groups" in other Dagstuhl seminars). A brief summary of the breakout sessions can be found in Section 4.

Advanced Runtime Analysis Methods. One difficulty common to the analysis of most randomized search heuristics is that, while in principle these are nothing more than randomized algorithms, their particular nature disallows the use of many methods used in the classical analysis of the randomized algorithms community. The particular difficulties include dealing with populations (instead of a single search point as in other local optimizers) or recombination (instead of mutation only, which creates a search point close to the parent). Both the fitness level method and various variants of the drift analysis method were greatly improved in the last three years to cope with these difficulties. Also, the fixed budget view on runtime analysis was recognized as an alternative way of analyzing the performance of randomized search heuristics, and may better reflect performance indicators used by practitioners.

Complexity Theory for Randomized Search Heuristics. Complexity theory is one of the corner stones of classical computer science. Informally speaking, the *black-box complexity* of a problem is the number of fitness evaluations needed to find its solution. Unfortunately, it turns out that some notoriously hard problems like the clique problem in graphs have a ridiculously small black-box complexity. In their 2010 GECCO award winning paper, Lehre and Witt presented a promising way out of this dilemma. They introduced a restricted version of black-box complexity that on the one hand still covers most known evolutionary approaches, but on the other hand forbids the counter-intuitive tricks that led to the undesired results in the first approach. Following up on this work, several variants of black-box complexity have been suggested. During the seminar, in particular during the breakout session on this topic, these were intensively discussed, new variations have been proposed, both from the theory perspective and from practitioners, and a new approach was presented explaining how to gain new and better evolutionary algorithms from black-box complexity results.

Theory of Natural Evolutionary Algorithms. Recently, the idea of conducting a natural gradient descent in the space of sampling probability distributions has been introduced in evolution strategies. The idea offers a very principled design technique for search algorithms that sample from a parameterized distribution. Comparable to classical deterministic optimization, an iterated gradient descent is performed on the distribution parameters. The remarkable difference is that the curvature information on this space is known a priori. A natural descent that is based on the inner product from the Fisher information matrix uses this curvature and is comparable to a Newton method. This new and promising idea is

lesser-known and largely unexploited for evolutionary computation. This is a completely new topic for this seminar series, but it is related to previous work on Covariance Matrix Adaptation.

Theory for Multi-Objective Optimization. One of the most explosive areas of growth both within evolutionary algorithms and in derivative-free optimization is multi-objective optimization. This is because good evolutionary algorithms now exist that can cover complex Pareto fronts for 2 to 12 objectives. This gives practitioners a much more informative view of the trade-offs that are possible when facing a multi-objective decision, and can also reveal trade-offs that otherwise would never be seen: for example if we are wishing to minimize cost and maximize quality, there can be "knees" at specific locations on the Pareto front where one might dramatically improve quality while incurring only a slight increase in cost. This is why multi-objective optimization methods that "map" the Pareto front are exciting. Yet, there is not a great deal of work on the theory of multi-objective optimization. Evolutionary algorithms are the method of choice for derivative-free multi-objective optimization and there is a great need to bring together theoreticians who are interested in evolutionary algorithms and those practitioners who are developing multi-objective optimization methods. This was another new topic for this seminar series.

Landscape Analysis. Landscape Analysis is an old idea: one should be able to compute features of a search space that can be used to guide search. One of the problems is that the kinds of metrics that one might wish to know about usually take exponential time to compute exactly. However, recent work has shown that some NP-hard problems (TSP, Graph Coloring, MAXSAT) can be decomposed to the point that Fourier methods can be used to exactly compute statistic moments of the search space (and subspaces of the search space) in polynomial time; these computation normally require exponential time for arbitrary problems. How can this information be used to guide the search, and to potentially replace heuristics with more exact information? New results in this area open new opportunities for exploration at this seminar series.

2 Table of Contents

3 Overview of Talks

3.1 Linear Convergence of the Isotropic ES via a Continuous Time Approximation

Youhei Akimoto (Shinshu University, JP)

An evolution strategy with isotropic Gaussian distribution derived from the information-geometric optimization (IGO) framework is studied on a composite of any strictly increasing function and a convex quadratic function and on a composite of any strictly increasing function and a twice continuously differentiable function. By extending the so-called ordinary differential equation (ODE) method, which is usually employed in the theory of stochastic approximation, we prove the linear convergence of the evolution strategy toward the global or local optimum.

3.2 The Dynamical Systems Approach Applied to the Analysis of Evolution Strategies for Constrained Oprimization

Dirk V. Arnold (Dalhousie University, CA)

We present a concise review of the dynamical systems approach to the analysis of adaptive optimization algorithms. We then discuss results obtained using that approach to study the behaviour of evolution strategies for constrained optimization. As test problem classes we consider a linear problem with a single linear constraint as well as a linear problem with a conically constrained feasible region for which the optimal solution lies at the cone's apex. The interaction of cumulative step size adaptation with two simple constraint handling techniques is examined, and significant differences in the results obtained are analyzed.

3.3 Sampling from Discrete Distributions

Karl Bringmann (MPI für Informatik – Saarbrücken, DE)

In a classic sampling problem we are given probabilities $p_1, \ldots, p_n$ (summing up to 1) and want to sample from the input distribution. This problem comes up in evolutionary algorithms when we want to select random parents for crossover proportional to their fitness or rank. We review a classic solution by Walker [1] building in linear time a data structure that allows to sample in constant time. Moreover, we give an overview of recent improvements and generalizations.

References

1 A. J. Walker. New fast method for generating discrete random numbers with arbitrary distributions. *Electronic Letters*, volume 10, pages 127–128, 1974.

3.4 What Information Can We Obtain Using Landscape Theory?

Francisco Chicano (University of Malaga, ES)

Joint work of Chicano, Francisco; Sutton, Andrew M.; Whitley, L. Darrell; Alba, Enrique

Landscape Theory is a mathematical framework with the purpose of getting some insight of Combinatorial Optimization Problems. Using Landscape Theory we can compute the Fitness-Distance Correlation [2], the expected value of the fitness function after a bit-flip mutation [4, 1] and the expected fitness after a uniform crossover [3]. In this talk we provide details on these expressions and present a new result: the computation of the probability distribution of the fitness after mutation. With this result we are able to compute the expected first hitting time of a (1+lambda) EA, which is probably the first connection between Landscape Theory and Runtime Analysis.

References

1 Francisco Chicano and Enrique Alba. Exact computation of the expectation curves of the bit-flip mutation using landscapes theory. In *Proceedings of Genetic and Evolutionary Computation Conference (GECCO 2011)*, pages 2027–2034, 2011.
2 Francisco Chicano and Enrique Alba. Exact computation of the fitness-distance correlation for pseudoboolean functions with one global optimum. In *Proceedings of EvoCOP*, volume 7245 of *LNCS*, pages 111–123. Springer, 2012.
3 Francisco Chicano, Darrell Whitley, and Enrique Alba. Exact computation of the expectation curves for uniform crossover. In *Proceedings of Genetic and Evolutionary Computation Conference (GECCO 2011)*, pages 1301–1308, 2012.
4 Andrew M. Sutton, Darrell Whitley, and Adele E. Howe. Mutation rates of the (1+1)-EA on pseudo-boolean functions of bounded epistasis. In *Proceedings of Genetic and Evolutionary Computation Conference (GECCO 2011)*, pages 973–980, 2011.

3.5 Updates from the Black-Box

Carola Doerr (University Paris-Diderot, FR)

Joint work of Doerr, Benjamin; Doerr, Carola; Ebel, Franziska
Main reference B. Doerr, C. Doerr, F. Ebel, "Lessons From the Black-Box: Fast Crossover-Based Genetic Algorithms," in Proc. of 15th Annual Conf. on Genetic and Evolutionary Computation (GECCO'13), pp. 781–788, ACM, 2013.
URL http://dx.doi.org/10.1145/2463372.2463480

Black-box complexity aims at establishing a complexity theory for evolutionary algorithms and other randomized search heuristics. We often observe that black-box optimal algorithms have a smaller runtime than the search heuristics that we regard. In contrast to those algorithms, evolutionary algorithms typically do not benefit from search points that are inferior to the current-best solution ("best-so-far solution"). In this talk we present a class of new genetic algorithms that are inspired by this paradigm. We prove that, for suitable parameter choices, the expected runtime of these algorithms is $o(n \log n)$ on OneMax. This is the first time that an asymptotic improvement for OneMax can be achieved by using crossover operators. The talk is based on joint work with Benjamin Doerr and Franziska Ebel.

3.6 Non-Elitist Genetic Algorithm as a Local Search Method

Anton V. Eremeev (Sobolev Institute of Mathematics – Omsk, RU)

Main reference A.V. Eremeev, "Non-elitist genetic algorithm as a local search method," arXiv:1307.3463v2 [cs.NE], 2013.
URL http://arxiv.org/abs/1307.3463v2

In this paper, the non-elitist genetic algorithms with tournament selection (denoted by GA in what follows) are compared to the local search methods on the class of the NP optimization problems [1]. It is assumed that the fitness function of a GA is identical to the objective function on the set of feasible solutions and the infeasible solutions are penalized. The operators of crossover and mutation are supposed to be efficiently computable randomized routines. The population size and the tournament size may depend on problem instance. In many well-known NP optimization problems the set of feasible solutions is the whole search space. We show that the GA with suitable parameters tuning first reaches a local optimum to such problems in O(1) iterations on average. The population size and the tournament size are assumed to grow linearly in $1/s$ and $\log(m)$, where s is a lower bound on the probability to transform any given solution x into any given solution in the neighborhood of x, and m is the number of non-optimal levels of objective function. Often some termination condition is used to stop a GA when a solution of sufficient quality is obtained or because the population is trapped in some unpromising area. To incorporate the possibility of restarting the search, we also consider an Iterated GA, where the basic GA is terminated and independently initialized every time after a given number of iterations. It is shown that if the NP optimization problem and the value $1/s$ are polynomially bounded and the initial population always contains a feasible solution, then the Iterated GA with suitable choice of parameters first visits a local optimum on average in polynomially bounded time. Besides that, it is proven that any problem from the class of problems with guaranteed local optima (GLO) [1] may be approximated within a constant ratio by means of the Iterated GA with bitwise mutation operator in polynomial time on average.

References

1 G. Ausiello, M. Protasi. Local search, reducibility and approximability of NP-optimization problems.*Information Processing Letters*, volume 64, pages 73–79, 1995.

3.7 Parameterized Average-Case Complexity of the Hypervolume Indicator

Tobias Friedrich (Universität Jena, DE)

Joint work of Bringmann, Karl; Friedrich, Tobias;
Main reference K. Bringmann, T. Friedrich, "Parameterized Average-Case Complexity of the Hypervolume Indicator," in Proceedings of 15th Annual Conf. on Genetic and Evolutionary Computation (GECCO'13), pp. 575–582, ACM, 2013.
URL http://dx.doi.org/10.1145/2463372.2463450

The hypervolume indicator (HYP) is a popular measure for the quality of a set of n solutions in $\mathbb{R}^d$.We discuss its asymptotic worst-case runtimes and several lower bounds depending on different complexity-theoretic assumptions. Assuming that P $\neq$ NP, there is no algorithm

with runtime poly(n, d). Assuming the exponential time hypothesis, there is no algorithm with runtime $n^{o(d)}$.In contrast to these worst-case lower bounds, we study the average-case complexity of HYP for points distributed i.i.d. at random on a d-dimensional simplex. We present a general framework which translates any algorithm for HYP with worst-case runtime $n^{f(d)}$ to an algorithm with worst-case runtime $n^{f(d)+1}$ and fixed-parameter-tractable (FPT) average-case runtime. This can be used to show that HYP can be solved in expected time $\mathcal{O}(d^{d^2/2}\, n + d\, n^2)$,which implies that HYP is FPT on average while it is W[1]-hard in the worst-case. For constant dimension d this gives an algorithm for HYP with runtime $\mathcal{O}(n^2)$ on average. This is the first result proving that HYP is asymptotically easier in the average case. It gives a theoretical explanation why most HYP algorithms perform much better on average than their theoretical worst-case runtime predicts.

3.8 Clustering as a Benchmark Optimization Problem

Marcus Gallagher (The University of Queensland, AU)

In recent years there has been increasing focus on improving the quality of experimental evaluations and comparisons of continuous evolutionary algorithms and metaheuristics. A good example of this is the Black-Box Optimization Benchmarking (BBOB) test problem suite and workshops. However, there is still alack of benchmark problems that are representative of real-world optimization problems. In this presentation, I discussed the data clustering problem in the 2-D Euclidean plane as potentially a very useful source of benchmark continuous optimization problems. Clustering is a fundamental problem in data mining and is also closely related to location-allocation problems from operations research. From a theoretical point of view clustering is an NP-hard problem and problem instances in practice are expected to present challenging features for algorithms. From a benchmarking point of view, clustering problems are unconstrained, simple to generate and have many properties that are desirable in benchmark functions. Random instances can be generated by generating datasets from a specified probability distribution. As an example, results were presented for clustering problems based on uniformly random data in the unit square. Using the standard k-means clustering algorithm, results confirm that problem instances have a large number of local optima and are challenging for black-box algorithms to solve. In addition,there appears to be a regime for the number of data points (n) and the number of cluster centers (k) where generated problems where k-means takes much longer to converge. An explanation of this observation is an open problem.

3.9 On the Analysis Approach of CSA on the General Ellipsoid Model

Michael Hellwig (Fachhochschule Vorarlberg, AT)

Joint work of Hellwig, Michael; Hans-Georg Beyer

The optimization behavior of evolution strategies (ES) applying cumulative step size adaptation (CSA) on convex-quadratic functions (referred to as ellipsoid model) is investigated.

The analysis considers $(\mu/\mu_I, \lambda)$-CSA-ES using intermediate recombination and isotropic mutations. Introducing the asymptotically exact quadratic progress rate the talk gives insight into a new analysis approach for the dynamical ES system. The dynamical system is modelled by a set of non-linear difference equations which describe the component-wise progress towards the optimizer, the mutation strength control as well as the change in the search path vector within the CSA. In the steady state the system can be transformed into an eigenvalue problem. Solving the eigenvalue problem allows for predictions of the ES systems behavior in the vicinity of the steady state. While the analysis is not yet complete the approach is validated by the good agreement of first theoretical predictions with experimental results.

3.10 Fixed Budget Computations: Why, How and What?

Thomas Jansen (Aberystwyth University, GB)

Run time analysis of evolutionary algorithms (EAs) is currently a dominating topic in the theory of EAs. It can be traced back 20 years, the last 15 years have seen a large number of publications that jointly have developed a wealth of analytical methods, surprising insights, and a better understanding of many aspects of EAs. However, these results are hardly appreciated outside the theory community. We argue that one reason is the lacking connection to the way EAs are applied in practice. Run time analysis is about the time needed to find an optimal or approximately optimal solution, something that is often not achieved in practice. In applications, evolutionary algorithms are more often stopped after some time. The assessment of the performance of EAs based on the expected function value after a fixed budget of function evaluations is closer to this way of applying EAs. We suggest this method as an alternative, discuss why we believe it offers a more useful perspective, how results in this framework can be obtained, and what the current state of the art is. The talk is mainly an open invitation to join us in the development of this novel research direction. This talks presents joint work with Benjamin Doerr, Carsten Witt, and Christine Zarges.

3.11 Some Runtime Analyses on the (1+λ) EA

Marvin Künnemann (MPI für Informatik – Saarbrücken, DE)

Joint work of Doerr, Benjamin; Künnemann, Marvin;
Main reference B. Doerr, M. Künnemann, "Royal road functions and the (1 + λ) evolutionary algorithm: Almost no speed-up from larger offspring populations," in Proc. of the 2013 IEEE Congress on Evolutionary Computation (CEC'1313), pp. 424–431, IEEE, 2013.
URL http://dx.doi.org/10.1109/CEC.2013.6557600

We study properties of Evolutionary Algorithms (EAs) with non-trivial offspring populations in the context of the (1+λ) EA. Already on linear functions, we observe that there are choices for the population size λ that yield, surprisingly, different asymptotic runtimes for the (1+λ) EA, more precisely for the prominent functions OneMax and BinVal. On the natural test function class of Royal Road functions, we show that a polynomial-sized offspring population

has a very restricted speed-up effect. We give some ideas of how to prove upper and lower bounds for the (1+λ) EA on these function classes. This talk summarizes joint work with Benjamin Doerr.

References

1 B. Doerr and M. Künnemann. How the $(1 + \lambda)$ Evolutionary Algorithm optimizes linear functions. In *Proceedings of Genetic and Evolutionary Computation Conference (GECCO 2013)*, pages 1589–1596. ACM, 2013.

2 B. Doerr and M. Künnemann.Royal road functions and the (1+λ) Evolutionary Algorithm: Almost no speed-up from larger offspring populations. In *IEEE Congress on Evolutionary Computation (CEC 2013)*, pages 424–431. IEEE, 2013.

3.12 Optimising Existing Software with Genetic Programming

William B. Langdon (University College London, GB)

Main reference W. B. Langdon, M. Harman, "Optimising Existing Software with Genetic Programming," accepted for publication in IEEE Trans. of Evolutionary Computation; authors' submitted version available.

URL http://www.cs.ucl.ac.uk/staff/W.Langdon/ftp/papers/Langdon_2013_ieeeTEC.pdf

We show genetic improvement of programs (GIP) can scale by evolving increased performance in a widely-used and highly complex 50000 line system. GISMOE found code that is 70 times faster (on average) and yet is at least as good functionally. Indeed it even gives a small semantic gain.

References

1 William B. Langdon and Mark Harman. Optimising existing software with genetic programming. *IEEE Transactions on Evolutionary Computation*. Accepted.

3.13 Random Declines and Drift Analysis

Johannes Lengler (ETH Zürich, CH)

Drift analysis has been a major tool for runtime analysis of Evolutionary Algorithms. For finite search spaces, they often come in pairs of matching upper and lower bounds. While the upper bounds hold in general, I present in my talk a class of Random Walks for which the standard lower bounds fail as the search space becomes infinite. In particular, the lower bounds known as "Variable Drift Theorems" fail although drift analysis still gives the correct runtime after a suitable transformation of the search space. Hence, the known Variable Drift Theorems need further improvement.

3.14 Runtime Analysis of Ant Colony Optimization on Dynamic Shortest Path Problems

Andrei Lissovoi (Technical University of Denmark, DK)

Joint work of Lissovoi, Andrei; Witt, Carsten;
Main reference A. Lissovoi, C. Witt, "Runtime analysis of ant colony optimization on dynamic shortest path problems," in Proc. of the 15th Annual Conf. on Genetic and Evolutionary Computation (GECCO'13), pp. 1605–1612, ACM, 2013.
URL http://dx.doi.org/10.1145/2463372.2463567

We consider the behaviour of a simple ACO algorithm called λ-MMAS on instances of dynamic shortest path problems where the optimum rapidly oscillates between two similar solutions. It is shown that reducing the evaporation rate ρ slows, but does not prevent, pheromone freezing when a single ant is started at each vertex. Starting a constant number of ants with a not-too-high evaporation rate allows the optimum solution to be constructed with constant probability in each of any polynomial number of iterations of certain easy problem instances. Additionally, the limitations of pheromone memory are demonstrated by considering an oscillation between two optimums that are not similar: while uncertainty about a specific choice can be represented in pheromone values, the memory cannot store distinct solutions.

3.15 Quantifying Optimization Problem Similarity Using Information Distance

Rachael Morgan (The University of Queensland, AU)

Quantifying the similarity between black-box optimization problems is important but non-trivial. In practice, there are two general methodologies employed: 1) problems are compared via measurements of particular problem properties/features (e.g. correlation length) and 2) problems are compared via the performance of algorithm instances. Ideally, a problem similarity measure should be a metric, estimated easily from data (with minimal loss of information) and able to compare problems of varying size and dimensionality. In addition, in the context of black-box optimization, such a measure is restricted to using only the information available in the black-box setting.

This talk proposed using the information distance – a universal distance – to measure the (dis)similarity between continuous optimization problems. While mainly a theoretical notion, the information distance can be approximated via the Normalised Compression Distance (NCD). NCD utilises standard compression algorithms to compute an approximation of the information distance between objects. Hence, by simply sampling the solutions and their respective objective function values of two optimization problems, the NCD between the samples can be used as a measure of distance between the problems.

To illustrate the proposed methodology, the NCD between circle packing problems and problems within the Black-Box Optimization Benchmark (BBOB) set were presented. The results showed that the similarity of the structures known to be within these problems is preserved by NCD. The results also demonstrated the use of Multi-Dimensional Scaling as

a technique to visualise the resulting NCD between problems, and hence, visualise where problems are located within the 'problem space'.

3.16 How to Bridge Theory and Practice in Supply Chain Management

Frank Neumann (The University of Adelaide, AU)

Joint work of Bonyadi, Mohammad Reza; Michalewicz, Zbigniew; Barone, Luigi; Ghandar, Adam; Neumann, Frank

We discuss the current gap in the area of evolutionary computation methods for large scale optimization problems arising in the area of supply chain management. Evolutionary algorithms have been widely applied to a wide range of classical combinatorial optimization problems such as the traveling salesman problem or the knapsack problem. We argue that real world problems differ from these classical NP-hard optimization problems significantly in complexity as real-world problems are composed of different (NP-hard) sub-problems and the increase in complexity is due to the combination of these problems. Hence, it is important to understand how different problems that interact can be solved by evolutionary computing methods. We argue that there is a strong need for new benchmarks addressing this current gap and point out by an example problem, based on the classical traveling salesperson problem and the knapsack problem, how such interactions look like. For theoretical research on evolutionary algorithms, we pose it as an open challenge to understand the interactions of problems by means of theoretical investigations. We point out open topics for research in the areas of runtime analysis and fitness landscape analysis. In the case of rigorous runtime analysis it would be desirable to have results that show how the runtime behaviour changes when combining sub-problems. Investigations in the area of fitness landscape analysis could reveal on how the fitness landscape changes when combining subproblems such as the traveling salesperson problem and the knapsack problem.

3.17 Parameterized Complexity Analysis and More Effective Construction Methods for ACO Algorithms and the Euclidean Travelling Salesperson Problem

Samadhi Nallaperuma (The University of Adelaide, AU)

Joint work of Nallaperuma, Samadhi; Sutton, Andrew M.; Neumann, Frank

We propose a new construction procedure for ant colony optimization (ACO) algorithms working on the Euclidean traveling salesperson problem (TSP) that preserves the ordering on the convex hull of the points in the instance. The procedure is inspired by theoretical analyses for simple evolutionary algorithms that are provably more efficient on instances where the number of inner points of the instance is not too large. We integrate the construction procedure into the well-known Max-Min Ant System (MMAS) and empirically show that it leads to more efficient optimization on instances where the number of inner points is not too high.

3.18 Run-time Analysis to Elucidate the Benefits of Crossover

Adam Prugel-Bennett (University of Southampton, GB)

Joint work of Prugel-Bennett, Adam; Rowe, Jonathan; Shapiro, Jonathan

In this talk we describe current work on obtaining run time bounds on a set of problems which demonstrate the benefit of crossover. We start by showing that an EA using a population of size $P = \Omega(n)$ can solve onemax in no more than $\sqrt{n}\log(n)$ generations with overwhelming probability. The EA works by pairing the parents and producing two complementary children using uniform crossover. The fitter of the two children is chosen. The pairing is done so that each parent is chosen twice, and paired with a different partner. We show that at each site there is a sufficient drift towards increasing the number of ones that fixation is exponentially unlikely and the expected run time is no more than $\sqrt{n}\log(n)$ generations. We then consider four problems to illustrate the different benefits of the use of a population with crossover. The first of these examines the ability to put together building blocks. We consider a concatenated trap function consisting of m traps of size k (so that $n = m \times k$). The trap functions have a fitness function which is a symmetric V-shaped function of the number of ones in each trap except for the all ones state which has an additional fitness of one. To ease the analysis we assume k is odd, We consider the EA hybridised with a local hill-climber. The hill-climber is always run until completion so the traps are either in the all ones or all zeros state. We run the hill-climber on the two children produced by crossover and choose the fitter of the two children after the hill-climber. The children therefore have strings where each trap is either in the local or global optimum. Uniform crossover does not change the traps value if the two parents are in the same local optimum. If one parent is in the all 1's optimum and the other in the all 0's for a particular trap, then after crossover one child will have more than half 1's and the other less than half 1's. After hill-climbing one child will be in the all 0's state and the other in the all 1's state for that trap function. This means the problem is identical to the onemax except the state of the trap plays the role of the binary variable. We can thus reuse the analysis for onemax. If we choose the traps sufficiently large (e.g. $k = \Theta(\sqrt{n})$) then a (1+1)-EA would take super-polynomial time while our algorithm solves this problem in $O(n^{7/4}\log(n))$. The second mechanism we study is the concentration of search by crossover. We consider a modified onemax with a plateau of size $g\sqrt{n}$ when there is an ones in a binary string ($a > 1/2$). We show that because it is quite likely for two children to differ in the number of ones by $\Omega(\sqrt{n})$, then with reasonable frequency the two children will span the gap and there will be a drift towards increasing the total number of ones. The drift is sufficient to ensure that the population will rapidly cross the gap. Once again we show that a (1+1)-EA will take super-polynomial time to cross the gap. The third mechanism we consider is the tolerance to noise of a population based EA using crossover. To illustrate this we consider onemax, but with a noise at each fitness evaluation drawn from a normal distribution, $N(0, n)$. We show that despite this noise the EA still has a significant positive drift towards increasing the number of ones, thus, with a very small modification we show that we can solve onemax with noisy fitness in $O(n\log(n))$. In contrast a (1+1)-EA will take super-polynomial time. The final mechanism (somewhat related to the previous), is the tolerance of our EA to local randomness. Here, we consider an objective function which is the sum of the onemax problem and a random function. The random function at each configuration is just chosen form a normal distribution, $N(0, n)$. The difference to the problem discussed above is that the noise is static or quenched in this

model rather than varying at each fitness evaluation. The objective is to find a solution with $(1-\epsilon)n$ ones (note that we have no guarantee as to where the actual global optimum is). We have no proof for our EA, however, we make the observation that if the minimum Hamming distance between strings were above δn for some $\delta > 0$, then as the number of potential children at each crossover is $\Omega(2^{\delta n})$, it is exponentially unlikely that a child will visit a configuration we have already visited (given that we have run for a polynomial number of generations). Thus with overwhelming probability this case will be identical to the dynamic noise case and we can solve it in $O(\sqrt{n})$ generations (we no longer need the $\log(n)$ as we only require to get within ϵ of the optimum). For a hill-climber and (1+1)-EA we can show that the expected run time is super-exponential. The $\log(n)$ in the bound can be dropped if the fitnesses were concentrated. We show this is highly plausible. For the case of quenched noise, we need to show that the Hamming distances are concentrated away from zero. The concentration is complicated, due to incest (children that share parents, grandparents, etc. will be more concentrated that those that don't). On the other hand, crossover rapidly mixes the members of the population, making it unlikely that the Hamming distances become very small. It remains an open problem to prove these concentration results.

3.19 Mathematical Landscape Theory

Peter F. Stadler (Universität Leipzig, DE)

Combinatorial landscapes are investigated with a focus on at least three different types of features: correlation measures, systems of adaptive or gradient walks, and the distribution of local optima. While all three approaches eventually provide insights into landscape ruggedness, their interconnections remain poorly understood. A connection between local optima and path systems is provided by coarse grained abstractions of the landscape, in particular its barrier trees representing local optima and their connecting saddle points [1, 2].

Typically, landscapes are viewed over a graph or metric space. This captures well search by mutation operators. Generalized closure operators allow to describe the topology of the search space induced by crossover-based search and may provide a meaningful way to study differences in landscape geometry arising from differences in search operators. An interesting variation on the idea of varying landscape geometry in algorithm design is to find biased embeddings in larger search spaces that are constructed in such a way that good solutions are enriched in the redundant representation [3].

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3.20 Analysis of Parallel Evolutionary Algorithms for Combinatorial Optimization

Dirk Sudholt (University of Sheffield, GB)

Joint work of Sudholt, Dirk; Lässig, Jörg; Neumann, Frank; Oliveto, Pietro; Rudolph, Günter; Mambrini, Andrea; Yao, Xin

We consider the speedup gained by island models in terms of the parallel running time for problems from combinatorial optimization: sorting (as maximization of sortedness), shortest paths and Eulerian cycles. The results show in which settings and up to what degree evolutionary algorithms can be parallelized efficiently. Potential speedups depend on many design choices such as the search operators, representations and fitness functions used on the islands, and also the parameters of the island model. In particular, we show that a natural instance for Eulerian cycles leads to exponential vs. logarithmic speedups, depending on the frequency of migration. We also discuss the use of crossover in island models for an instance of the VertexCover problem.

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3.21 Noisy Optimization in Continuous Domains

Olivier Teytaud (University of Paris South XI, FR)

Black-box noisy optimization is a great useful research area. Simple regret, cumulative regret, uniform rates, are various relevant criteria. We show that using second order information can improve the convergence rate of simple regret when noise is moderate; that sampling only around the optimum reduces the optimal convergence rates [1]; that ES are reasonably good in the case of cumulative regret [2].

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4 Breakout Sessions

After having successfully experimented with breakout sessions during the last edition of this Dagstuhl seminar, this time we made breakouts a substantial part of the seminar. After a public vote, both collecting preferences and scheduling conflicts, we decided to have the following breakout sessions, each lasting for around two hours, partially scheduled in parallel. The breakouts differed greatly in style and size, ranging from semi-plenary open problem sessions to half-a-dozen people discussing in-depth a specialized topic. The following notes, collected by session organizers or participants, try to collect the main points of each session.

4.1 Evolutionary Multiobjective Optimization

Dimo Brockhoff (INRIA Nord Europe – Lille, FR, dimo.brockhoff@inria.fr)
Joshua D. Knowles (University of Manchester, GB, j.knowles@manchester.ac.uk)
William B. Langdon (University College London, GB)

The breakout session on EMO during the Dagstuhl seminar 13271 "Theory of Evolutionary Algorithms" brought together people familiar with EMO and researchers who have not yet worked on multiobjective optimization. The main discussion topics included: open problems, Information Geometric Optimisation (IGO), interactive evolution (IE) in a Pareto optimal context, especially the practical role of not necessarily rational human decision makers subject to fatigue and business pressures. We also discuss the role of: external finite archives and elitism, crossover and mutation particularly in fixed binary and non-binary representations, drift analysis, reducing run time, LOTZ, two-sphere and other benchmarks and the SEMO algorithm. Our goal is to provide the basis from which concrete theoretical studies can rapidly emerge.

4.1.1 Introduction

Multiobjective optimization deals with optimization problems where two or more objective functions are to be optimized simultaneously and for which, typically, no single solution results in optimal values for all objectives. Instead, the search space exhibits a natural partial order ("Pareto dominance relation") with the so-called set of Pareto-optimal solutions as its minima. For tackling multiobjective optimization problems with the use of evolutionary computation approaches, the term Evolutionary Multiobjective Optimization (EMO) has been coined. Although several theoretical studies in the field of EMO have emerged in recent years, fundamental questions are still open.

4.1.2 Overview

The EMO breakout session took place in the afternoon (4pm–6pm) of the second day of the Dagstuhl seminar (July 2, 2013) and was attended by Karl Bringmann, Dimo Brockhoff, Ken De Jong, Benjamin Doerr, Carola Doerr, Josephine Doerr, Joshua D. Knowles, Marvin Künnemann, W. B. Langdon, Jörg Lässig, Samadhi Nethmini Nallaperuma, Günter Rudolph, Manuel Schmitt and Lothar Thiele.

Most of the topics discussed during the breakout session originated from theoretical studies by some of the participants or from plenary presentations given during the first two days of the Dagstuhl seminar. The discussions related to Information Geometric Optimization,

interactive EMO, and runtime analyses were the longest and most lively and so will be described in detail particularly focusing on the open questions which were identified.

4.1.3 Information Geometric Optimization and Multiobjective Optimization

Information Geometric Optimization (IGO) [12] is a recently proposed canonical and systematic way of looking at single-objective black-box optimization problems. The so-called *IGO flow*, a general continuous-time model of a black-box optimization algorithm, thereby optimizes the parameters of a given family of probability distributions by following the direction of the natural gradient of a joint optimization criterion posed on the manifold of probability distributions. It inherently possesses several invariance properties such as "invariance under reparametrization of the search space, under a change of parameters of the probability distribution, and under increasing transformation of the function to be optimized" (see [12]). Discretizations of the IGO flow for specific families of probability distributions result in known algorithms such as the CMA-ES [13], xNES [4] and PBIL [1].

As the IGO flow formulation is very general, the natural question is whether and how this would be formulated for multiobjective optimization problems and most importantly, which algorithms would emerge by the discretization of the (multiobjective) IGO flow.

One first step towards an answer, discussed during the breakout session, was to start with the simplest possible probability distribution for sampling *sets* of solutions: define μ linked probability distributions, one per member of the EMO algorithm's population, with μ the population size. In order to transform the set problem back to the IGO framework, one could use for example the hypervolume indicator of the set as the scalar objective function. As underlying family of probability distributions, we should probably start with the simplest ones (either Gaussian distributions in the case of continuous search spaces or Bernoulli distributions in case of pseudo-Boolean search spaces). It was suggested that it might help to start with a concrete problem as this might help gain intuition into possible future algorithms, e.g. the double sphere ($f_1(x) = |x|^2, f_2(x) = |x - a|^2$ with $x, a \in \mathbb{R}^n$). In this problem, the goal is to minimise both f_1 and f_2. This naturally leads to the need to trade off f_1 and f_2 when $a \neq \vec{0}$.

4.1.4 Analyses of Interactive EMO Algorithms

Evolutionary multiobjective optimization algorithms typically aim at finding a set of solutions that approximates the set of Pareto-optimal solutions. However, in the real world not all of the Pareto-optimal solutions are equally interesting. Often, where there is a single customer, a single solution has to be picked eventually by a human decision maker (or a group of decision makers)—corresponding to the *most preferred alternative*. Even where there are many customers, they may not pick solutions from the whole range of Pareto-optimal solutions. Since there is no information about the acceptable trade-offs between the objectives the definition of the preferred solution before the search is often too difficult. Similarly after the search, and making one final choice within an overwhelmingly large number of solutions can be equally difficult. *Interactive EMO algorithms* have been recently proposed to reduce the user load inherent in EMO algorithms presenting many potential Pareto-optimal solutions to the users (see for example [7] for an overview). These interactive EMO algorithms ask the decision maker during the optimization to provide certain information about their preferences, e.g., to say which of two solutions is preferred. The algorithm tries to focus the search on search space regions "preferred" by the decision maker instead of finding an approximation of the entire Pareto front.

The first theoretical analysis of such an interactive EMO algorithm appeared last year in [3] in which not only the runtime of simple interactive EMO algorithms on pseudo-Boolean test functions have been investigated but also the expected number of times, the decision maker is required to interact until the most preferred solution is found. After a brief informal presentation of the paper's content, the discussion centered on how to extend this preliminary study towards more realistic algorithms and decision making scenarios.

One line of suggestions focused on the decision maker who typically is not always deciding rationally. To investigate more realistic cases, analysis of the decision maker behavior might involve noisy decisions, additional (hidden) objective functions, current decisions that depend on previous ones (i.e., a "learning" decision maker), or the unavailability of the decision maker at certain times. Another interesting aspect that came up in the discussion was to allow the decision maker to also say "I don't know" or "I don't care" for certain questions asked. (NB. these are not identical replies.) Developing algorithmic strategies for dealing with such scenarios and analyzing their impact on the search abilities theoretically is definitely an interesting open problem for the near future.

Another suggestion was to analyse interactive EMO algorithms on more complicated problems. A possible next step is the bi-objective spanning tree problem [14].

4.1.5 Runtime Analyses of EMO Algorithms

Though theoretical runtime analyses of single-objective optimization algorithms is now established, runtime analyses of multiobjective algorithms remain comparatively sparse. Therefore, more basic questions remain open than in the single-objective case. Open questions collected and topics discussed during the session include:

- the fundamental question of when crossover is helpful before reaching the Pareto front,
- whether drift analysis has been used for multiobjective optimization (yes, for example in [5]),
- whether problems exist where the known lower bounds on the expected runtime match the upper bounds when global mutations are allowed (so far no, to the best of our knowledge), or
- which other algorithms could "improve" the runtime on the LOTZ problem [9] when compared to the SEMO algorithm [8].

4.1.6 Archiving and Non-Standard Search Spaces

Finally, two other aspects of EMO were discussed during the breakout session: archiving and non-standard search spaces.

In terms of archiving and performance guarantees, the question came up of how non-elitist and comma-strategies can be analysed in the multiobjective case. For example, in terms of the quality of an external archive of pair wise non-dominated solutions. Similarly what is the impact of a finite limit versus allowing the archive to grow indefinitely? The general question of how to deal with finite size archives was discussed briefly and it was acknowledged that although there is work on convergence and quality [2, 10, 6], there is no consensus model or framework for analysis as yet.

In terms of non-standard search spaces (e.g. discrete, but not bit string $\{0,1\}^n$), the general question came up which properties of mutation operators are desired (cf. for example [11]), which is especially open for *mutation operators on solution sets*. Also theoretical studies comparing different mutation operators might be interesting to practitioners.

4.1.7 Conclusion

Several theoretical studies of evolutionary multiobjective optimization (EMO) algorithms and techniques have been published recently, but various fundamental questions remain open. The breakout session on EMO during the Dagstuhl seminar "Theory of Evolutionary Algorithms" (July 2013) brought together researchers interested in theory and multiobjective optimization and provided a good opportunity to collect several of those open questions and start a discussion about how to tackle them. The brief description of those discussions, provided here, can be used as a basis for future (joint) theoretical research in the growing field of Evolutionary Multiobjective Optimization.

4.1.8 Acknowledgements

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4.2 Black-Box Complexity

Carola Doerr (University Paris-Diderot, FR)

The breakout session on black-box complexity brought together researchers with much different interest in this topic. We discussed in the first 30 minutes our motivation for studying black-box complexity. While black-box complexity is mainly interesting as a tool to derive fairly general lower bounds for the optimization time of evolutionary algorithms and other randomized search heuristics for some, its main benefit is seen to be a source for inspiration in algorithmic design for others.

The participants in the discussion agreed that it would be nice to see as a future development black-box complexity results that go beyond the studies of the OneMax test functions. While the latter is an interesting source for inspiration and has imposed several beautiful questions and results in the last 50 years, it is important also to explore the black-box complexities of more intricate test beds, e.g., combinatorial optimization problems.

Johannes Lengler presented a new black-box algorithm that is built on the idea that offspring should be sampled not too far from the optimum. He explains that many optimal black-box algorithms gather a lot of knowledge about the problem at hand by consciously sampling non-optimal search points. This raises the question whether or not the black-box complexity necessarily increases when algorithms are allowed to sample only in a suitably chosen neighborhood of the search points that have been evaluated so far. While very restrictive neighborhood definitions will clearly lead to an increase in black-box complexity, recent progresses in algorithmic design seem to suggest that this is not the case for a more relaxed neighborhood structure. Johannes presented a new algorithm that has running time $o(n \log n)$ on the OneMax test functions. Also the algorithm by Benjamin Doerr, Carola Doerr, and Franziska Ebel [1] that was presented in a talk preceding this session achieves this. Benefits and drawbacks of both algorithms were discussed.

The participants agreed that transferring results from optimal black-box algorithms to the design of new evolutionary algorithms is a promising research direction. At the same time, the quest for a suitable black-box model continues. Several recent attempts, including memory-restricted, ranking-based, and unbiased versions of the black-box model seem to be a step in the right direction. However, in particular for algorithms using operators of arity strictly larger than one, a suitable black-box model is still missing. One potential model that was discussed during this breakout session is a "blind" version, where algorithms are given the fitness of the search points but no hint whatsoever about the search point itself. This version is related but not identical to the unbiased black-box model of Lehre and Witt [2].

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4.3 Natural Gradient

Nikolaus Hansen (INRIA Saclay – Orsay, FR)

An evolutionary search and optimization process can be described by an iterative update of a probability distribution over the space of candidate solutions. The fact that search and adaptation is accordingly conducted in the space of distributions is often not considered, and the algorithms and their analysis do not usually exploit the properties of this rather well-defined space. They use, for example, strategies rooted in standard Euclidean geometry, however, the space of probability distribution calls for a different mathematical treatment, which is investigated in the research field of information geometry. Information geometry is a rather young mathematical research field pioneered by S.-I. Amari. It has been successfully applied to computational learning problems. In particular, this way of thinking suggests replacing the gradient in Euclidean space by the gradient defined in the space of probability distributions – the so called natural gradient.

Independently from the work in the learning community, information geometric randomized search algorithms have been developed just recently. First, the natural evolution strategy was proposed. Then it was shown that the popular covariance matrix evolution strategy (CMA-ES) can be derived from an information geometric perspective. These new developments open the door to new theoretical insights into randomized search in general.

In the breakout session, different types of evolutionary algorithms using information geometric concepts were discussed. Similarities and differences between the approaches were outlined, ideas between people specialized in discrete and continuous search spaces, respectively, were exchanged. The open questions and next steps in this new research direction were discussed. Important problems were identified: first, the observation that actual behavior of the iterative algorithms often differs from the behavior predicted by the analysis of the corresponding time-continuous flow (along the natural gradient). Second, the fact that the algorithms most successful in practice update their parameters describing the probability distribution in a non-uniform way in the sense that, for example, the CMA-ES has different leaning rates for the mean and the covariance – although the information theoretic interpretation (in terms of following the natural gradient) suggests that all parameters should be updated in the same way. Furthermore, the question of how to extend the existing theoretical frameworks to multi-objective optimization was discussed.

4.4 Fixed Budget Computations

Thomas Jansen (Aberystwyth University, GB)

The breakout session about fixed budget computations was a well attended and lively session that turned out to concentrate mostly on collecting open problems and questions that we would like to see answered. Participants in the discussion were Dimo Brockhoff, Kenneth A. De Jong, Benjamin Doerr, Carola Doerr, Thomas Jansen, Daniel Johannsen, Timo Kötzing, Joshua D. Knowles, Johannes Lengler, Frank Neumann, Jonathan E. Rowe, Dirk Sudholt

and Christine Zarges. Notes have been taken by Dimo Brockhoff and Dirk Sudholt. These notes are the basis of this summary.

Currently, fixed budget results concentrate on very simple algorithms like random local search and the (1+1) EA [1, 2]. However, there is consensus that a wide range of algorithms should be analysable and be analysed. It is remarked that hybrid algorithms (e. g., memetic algorithms) may be of particular interest.

There is a wide range of different results that are desirable. Among them are results for large ranges of budgets; average case results; relative results for the comparison of algorithms; results for algorithms with high variance in performance (a kind of algorithms for which currently there are no good methods to deal with them analytically); results that highlight the influence of the selection pressure for a fixed budget; results on optimal algorithms (in the terms of black-box complexity); results for multiple runs, in particular for parallel runs; results for NP- hard combinatorial optimisation problems (similar to optimisation time results for PARTITION [3]) where results about structural properties of the problem instances would be of particular interest; results for FPT problems with fixed n depending on k; precise results for fixed n in general; results for dynamic fitness functions; and results for functions defined over continuous domains. It is pointed out that one should concentrate on proving lower bounds and that it is probably advisable to be more generous with respect to changes of the budget.

There is an open debate if making statements about the expected function values is actually the most useful thing to do. It may be more interesting to make statements about the median or quantiles instead of the expectation. Also rank-based results may be more meaningful than statements about the function value. An important aspect is the robustness (or brittleness) of results with respect to changes of the considered algorithm or problem.

For future analyses it is desirable to develop more analytical tools. Coming up with a method based on fitness levels appears to be a reasonable first step. It is open how fixed budget results can be obtained in general without revisiting optimisation time results. It is also open if and how results from landscape theory can help.

Another more general aspect that was also discussed was concerned with the goal of this kind of research, about the things that we want to see achieved. One obvious positive outcome would be novel insights that lead to the design of better search heuristics. Specific aspects are the design of stopping or restart criteria and the question of resampling when dealing with noisy fitness functions. A perhaps obvious application would be in algorithm portfolios where algorithms could be combined based on the relative strength in different epochs of the search. Less concrete but still useful would be a better understanding of the balance of exploitation and exploration in heuristic search. Another fruitful goal would be to address contradictory results between theory (in the sense of optimisation time) and practice, hopefully leading to more meaningful theoretical results. It can also be hoped that more useful notions of when one algorithm is better than another can be obtained.

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4.5 Theory and Practice and Co-Evolution

William B. Langdon (University College London, GB)

Present: Christine Zarges, Manuel Schmitt, Rachael Morgan, Samadhi Nethmini Nallaperuma, Frank Neumann (FN), Ken de Jong (KDJ), Thomas Jansen, Jon Shapiro, Lothar Thiele, W B Langdon (WBL), Joshua D Knowles, Marcus Gallagher, Darrell Whitley (DW), Tom Schaul, Francisco Chicano.

The session was held outside with Frank Neumann interested in how theory helps with applications, particularly with respect to the Travelling Thief Problem TTP proposed at CEC 2013 by Zbigniew Michalewicz. KDJ suggests Michalewicz should provide abstraction of his real world problem that theory community can deal with.

FN described Travelling Thief Problem and KDJ suggested it be posed (and solved?) as a coevolutionary problem in which Travelling Salesman Problem (TSP) be viewed as one problem to be dealt with by one population and a cooperative population deal with second part. The second part being treated as knapsack problem. The two populations would each solve their part with the cooperation of members of the other population.

FN discussion of whether TTP is multi-objective problem or single objective. FN might propose a variant of TTP as a competition at GECCO or CEC.

Thomas Jansen said exact theorems are available for 1+1 coevolutionary algorithms

There was a general discussion of how (if at all) two known problems can be combined in such away that knowledge helps solution of new problems.

Jon Shapiro provided a counter example: two polynomial problems on graphs (one uniform colouring the other majority? colouring) can be combined to create an NP hard problem.

KDJ suggested what was needed was way of combining two NP hard problems to get a polynomial problem.

KDJ said Elena Popovici's work on coevolutionary landscapes suggests combining two problems can lead to vary different behaviour depending upon details of parameter settings. In coevolution very important to retain diversity. A good strategy is to retain memory of trial solutions off to the side, ie, in addition to the evolving populations.

Lothar Thiele suggested coal supply sub-problems interact via shared variables.

Bill Langdon (WBL) suggested that by taking the coevolutionary route we were mandating the two sub-problems be represented by sticking their two representations side by side. This may work, it may be easy, but by doing so we rule out all other possibilities.

Joshua D Knowles suggested reconsidering Richard Watson's HIFF problems. And also the biological literature on symbiotic evolutions.

Marcus Gallagher asked whether solving first instance give you an instance of the second problem. FN suggested if we fix a picking list (ie contents of the knapsack) it determines the TSP to be solved.

WBL said the picking list changes to the TTP "velocity" can be thought of as increasing the distance between cities in the TSP. Redrawing the TSP map. Darrell Whitley said

also equivalent to needing more petrol between cities when have place heavy items in the knapsack.

DW said if we look at OR community, first rate results are obtained only by domain experts with say 20 years experience. These guys are not doing black-box optimisation, they are using their domain knowledge.

KDJ mentioned Christine Mumford's (http://users.cs.cf.ac.uk/C.L.Mumford/) work on collecting time tabling examples for use as useful benchmarks.

KDJ wondered if a useful problem might be to consider a direct graph (DAG) where the nodes were labelled with (randomly generated) problem instances. Solutions of each node's problem become inputs to the problems located at the node's children nodes.

DW recounted problem with academic job shop scheduling (JSS) benchmarks. Industry disregards these (and hence academic research) because they are tailored uniform randomly generated, whereas industrial problems are not uniform. DW said these benchmarks are worse than useless. If replaced by non-random problems the techniques that do best now do the worst. Introduction of tailored benchmarks has harmed the field.

WBL described his experiments on getting genetic programming to create benchmarks (IEEE TEC doi:10.1109/TEVC.2006.886448) in which a state of the art EA was defeated by a no-frills particle swarm optimiser (PSO). Also GP generated a search problem where the EA beat the PSO.

Lothar Thiele was interested in what theoretical analysis tells us.

KDJ recalled Toby Walsh's keynote at FOGA 2013: http://www.sigevo.org/foga-2013/keynote.html.

DW talked about "backbone" of solutions to SAT like problems and said TSP does not have such a backbone. DW then briefly described his Walsh analysis of k-SAT and how if leads in $O(n)$ time to the problem's backbone and hence rapidly to solutions. WBL this is an instance of theory driving algorithm design (rather than the reverse).

Francisco Chicano spoke in favour of theory helping to design algorithms. DW says applies to all pseudo Boolean problems (pretty big class).

4.6 Landscape Analysis

Adam Prugel-Bennett (University of Southampton, GB)
L. Darrell Whitley (Colorado State University, US)

The session discussed new methods for characterising problem hardness. Over the last 20 years one focus of landscape analysis has centred on elementary landscapes. However, these properties, such as the autocorrelation function, are identical for the same problem class for easy instances and instances which are found in practice to be very hard to solve. Thus, there is a need to find new measures. There is some promise in looking at the "superposition" of elementary landscapes. This works from domains such as pseudo-Boolean functions, and provides new statistic information about subregions of the search space. But there is still a challenge to leverage this information in useful ways. For k-bounded pseudo-Boolean functions, Walsh analysis still holds promise as a means of tracking the nonlinear interactions between variables; understanding these nonlinear interactions is key to understanding how to exploit improving moves on neighborhood structures.

It is possible that landscapes are so varied that finding a single property which captures problem hardness is a fruitless exercise, nevertheless there are many regularities found in a large class of problems when viewed at a large scales. In particular they tend to show similar distribution of local optima weakly correlated with a global optimum. Often there were regularities which were not immediately obvious. One new line of possible research is to use parameterised complexity and possibly some approximation to that idea to isolate the true complexity. Another idea is to search for structure in the distribution of local optima using principal component analysis to capture the major directions in which the local optima vary. Early investigations show that there is a lot of regularity which is easily missed. This raised the question of how these regularities could be exploited. In this regards we discussed the great success of crossover on many classic optimisation problems and tried to understand how this could be understood in terms of the landscape structure. We also discussed some recent ideas on modelling problems in terms of Gaussian Process models with the same mean fitness and two point correlation function as a real world problem.

4.7 General Drift Analysis with Tail Bounds

Jonathan E. Rowe (University of Birmingham, GB)

The discussion centred around two open questions in drift analysis. Firstly, the recently discovered flaw in the "negative drift" theorem. Secondly, whether or not tail bounds could be derived in the general variable drift case.

For the first part, it was noted that a fix for the problem has been proposed – namely disallowing large moves even away from the target. While this works (i.e. we get a proof), in some ways it seems not necessarily helpful, since there may be situations where there are large moves away from the target in which we would like to apply the theorem. A range of potential alternative conditions were suggested, and it was left for further work to pursue these for those interested.

For the second part, we looked at the problem of how tail bounds in the constant or multiplicative drift scenario might be transformed with the change of variable given by the variable drift theorem. It seemed that some progress could be made along these lines. Per Kristian Lehre told the group that indeed this could be done and some new results were shortly to be published on arxiv.

4.8 Parallel Evolutionary Algorithms

Dirk Sudholt (University of Sheffield, GB)

The aim of this breakout session was to discuss the theory of parallel variants of evolutionary algorithms. A previous talk by Dirk Sudholt (Section 3.20) about the analysis of parallel EAs for combinatorial optimization served as a primer.

At first, Bill Langdon gave a short introduction to parallel hardware: from multiple CPU cores with shared memory to parallel implementations on GPUs using CUDA and clusters

of machines using MPI and message passing for communication. This led into a discussion about what is the right performance measure regarding the communication costs between parallel populations in island models – a question that arose during the previous talk. The importance of this criterion varies strongly between architectures, but it was generally agreed that the number of packets sent between islands was a sensible measure, and that typically migrants sent out would fit into one packet. Kenneth De Jong pointed out that in some architectures setting up the parallel system can be very costly.

In the remainder of the session the participants engaged in an open, inspiring, and sometimes controversial discussion around various aspects in the design and theoretical understanding of parallel EAs. Questions discussed include the following.

When do island models behave differently from panmictic populations? (Kenneth De Jong made the point that with frequent migrations island models take on characteristics of panmictic populations. Bill Langdon contributed a rule of thumb saying that there is a threshold behaviour at sending one individual per generation on average. Dirk Sudholt explained a theoretical result [2] on a problem where island models with migration outperform panmictic populations as well as independent runs.)

What is the right way of comparing a panmictic EA (e.g. a (100+100)EA) against a parallel EA with several subpopulations (e.g. 10 islands reach running a (10+10)EA)? (One conclusion was to keep the number of function evaluations the same for both settings.)

During migration, should individuals be removed from their original population, or should copies thereof be sent? How to choose migrants to be sent?

Should islands send migrants to all neighbouring islands probabilistically, or pick one island chosen uniformly at random? (The following discussion showed that the analysis method from [1] is applicable to various such settings.)

How can we deal with settings where nodes might fail and not respond, or have random response times?

Can we derive fixed-budget results for parallel evolutionary algorithms to show that parallelisation can lead to better solution quality?

How can diversity in parallel EAs be increased?

A final question was what theoretical results everyone would like to see in the future. Frank Neumann's answer was theoretical results that are closer to practice.

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Report from Dagstuhl Seminar 13272

Computer Science in High Performance Sport – Applications and Implications for Professional Coaching

Edited by

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Abstract

This report documents the program and the outcomes of Dagstuhl Seminar 13272 "Computer Science in High Performance Sport – Applications and Implications for Professional Coaching". There were 25 presentations organized into 5 sessions over the course of three days focusing on various aspects on the relevance, applications and current issues pertaining to computer science in sport and it's applications for professional coaching. Each session covered miscellaneous topics that looked at its broad topics ranging from hardware devices for mobile coaching, modelling sports as dynamical systems, use of neural networks in performance analysis as well as theoretical issues in human movement science, and serious games. Once again the Dagstuhl seminar concept provided benefits for the experts from different fields and countries that otherwise would hardly meet and have the opportunity to exchange their ideas in an informal way. Several ideas were presented aiming to reduce the gap between sport science and high performance coaching. New projects were discussed among the participants, such as the agreement to build a data repository in order facilitate the collaboration between different institutions with common and complementary research topics or framework in performance analysis.

Seminar 30. June to 03. July, 2013 – www.dagstuhl.de/13272

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1 Executive Summary

António Lopes

From June, 30th to July, 3rd, 2013 a seminar on "Computer Science in High Performance Sport – Applications and Implications for Professional Coaching" was held at Schloss Dagstuhl – Leibniz Center for Informatics. After 2006, 2008, and 2011 this seminar was the fourth on computer science in sport that was held in Dagstuhl.

Following the tradition, this seminar brought together experts from computer science together with experts from sports science to explore the options of interdisciplinary work.

This year emphasis was put on the interface between computer science and the high performance sport, in particular on coaching. The seminar focused on barriers that prevent coaches from embracing sport and computer science, and, how data can be presented in a more meaningful way so that coaches' expertise is enabled by science.

During the seminar, several participants presented their current research lines, ongoing work and open problems were discussed, focusing on three sub-themes: (1) coach-specific computer applications to address issues of communication and real-time application, (2) the pipeline from data acquisition to processing to analysis to visualization, and (3) modelling and simulation.

Twenty-seven invited participants, among which there were sports and computer scientists and coaches, gave a total of 25 talks and had enriching discussions about sport science. Problems, solutions, and benefits between computer science and sport science into high-performance coaching were discussed, and considered current developments in data acquisition, positional tracking, filtering, signal processing, game modelling, match analysis, performance analysis and optimization, computer-supported training, computer visualization and communication, 3D motion reconstruction, and serious games.

Abstracts of the presentations given during the seminar as well as abstracts of seminar results and ideas are put together in this paper. The first section describes the seminar topics and goals in general.

Once again, the Dagstuhl seminar concept provided benefits for the experts from different fields and countries that otherwise would hardly have met for an opportunity to exchange their ideas and inspire visions for the future of computer science and sport science in professional sport and coaching in an informal way. Several ideas were presented to reduce gap between sport science and high performance coaching and new projects were discussed among the participants. Discussion led to current and future trends and challenges that require implementation on high performance sports coaching, such as: mobile computing, multimedia, data visualization, performance reconstruction and real time feedback.

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3 Overview of Talks

3.1 Intelligent Systems

Arnold Baca (University of Vienna, Austria)

Joint work of Baca, Arnold; Kornfeind, Philipp; Tampier, Martin

Athletes and coaches require effective methods to support and guide the training process. Our approach is based on a feedback system providing mobile and almost real time solutions for wireless body sensor data transmission, processing and feedback provision. The concept of the system [1] helps to adapt and evaluate certain performance parameters in respect to the individual performance level. Characteristic parameters of the physical activity can be supervised continuously. In this way coaches are able to guide a number of athletes individually and the athletes get feedback of the quality of their motion which helps to interpret the body's reactions to physical load. For such purposes, sensors, carried by the person or mounted onto the sports equipment, are used to measure different parameters of an exercising person. These parameters are sent to a smart phone application via ANT+^{TM}.

The measured data is then transmitted to an application server using wireless communication technologies (UMTS, HSUPA). Based on the collected data feedback instructions can be generated by experts and sent back to the exercising person [2]. Sub-modules are currently integrated into the server application thus implementing intelligent algorithms for processing the acquired data. In this way feedback instructions may automatically be generated. The actual implementation of the system for running, for example, includes an intelligent feedback module for guiding further execution [3]. Load-based performance development is predicted by applying the antagonistic meta-model PerPot [4].

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3.2 Monitoring load and recovery in sports

Michel Brink (University of Groningen, the Netherlands; Hanze University of Applied Sciences, Groningen, the Netherlands)

Joint work of Lemmink, Koen

This talk will focus on the delicate balance between load and recovery in sports. In order to improve performance athletes continuously challenge their personal boundaries. This may

lead to a local or general overload of the human body that results into injuries, illnesses or the overtraining syndrome.

Monitoring load and recovery possibly may help to optimize performance and prevent athletes from health related problems. A theoretical framework that contains physical and psychosocial load and recovery components is presented. It is suggested that the total amount of load should be in balance with the total amount of recovery for optimal performance. Analyses could focus either on a comparison of individuals to their peers or a comparison with personal history data. Careful documentation of load, recovery and performance, by means of logs, questionnaires and field tests, seems a useful approach to detect a disturbed balance and guide intervention strategies.

3.3 Monitoring training in team sports: An example from professional team sports

Aaron Coutts (University of Technology, Sydney, Australia)

A major challenge for scientists working with professional team sports is being able to individualize training to meet the needs of both the individual and team. Due to the unpredictable nature of team sports, the training requirements of individuals within the same team can be diverse (i.e., dependent upon positional roles, recovery rates, experience etc.), and often requires careful monitoring and control so that performance is optimised. This is particularly relevant during periods of regular competition where the risk of maladaptive training is increased, and small changes in athlete readiness status can affect individual and team performance. Indeed, research has shown that overreaching can occur in team sport athletes with only a relatively small increase in the training load above what is considered "normal". Therefore, an important issue for the coach/scientist is having access to monitoring systems that accurately assess how players are coping with training and responding to training and match stimuli [1].

In this presentation, a theoretical model for monitoring team sport athletes will be provided. Additionally, we will provide a working example of current monitoring tools used in team sports, discuss logistical issues in implementing such a system, and present practical models of how data can be analysed to provide accurate and timely feedback to coaches. These will be supported by examples demonstrating how this approach has been used to inform coaches how athletes are coping with training and then used to guide decision-making about future training. Discussion of the role of computer science in modelling training responses and predicting performance and injury risks will be provided.

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3.4 The interpersonal coordination dynamics underlying individual and team tactical behaviours in soccer

Ricardo Duarte (TU Lisbon, Portugal)

This communication will join some different studies under development illustrating the general framework we are using to capture individual and team tactical behaviours in soccer. As a general idea, we use player positional time-series data in order to analyse the interpersonal coordination tendencies than underlie the emergence of tactical behaviours. But, how can one transform these data into meaningful information? One way to capture the interpersonal coordination dynamics is using compound positional variables integrating relevant physical constraints associated to the performance field.

In respect to individual tactical behaviours, our efforts have been directed to determine the different performance profiles according to playing positions. Player-to-locus distance, the individual dominant region areas and the number of intra- and inter-team local spatial interactions showed important differences between playing positions. The defensive players and the inner midfielders showed less mean player-to-locus distances. Also, from defenders to forwards and from internal to external positions, there was a decrease in the number of local spatial interactions with teammates and an increase in the number of local spatial interactions with opponents. Inner midfielders displayed the lower areas but the higher total number of local spatial interactions.

In regards to team tactical behaviour, some compound positional variables such as surface area, stretch index, team width, team length, contraction-expansion speed and collective velocity have been used to capture specific team tendencies. Nowadays, we are integrating these continuous variables with some categorical variables such as having or not ball possession and the corresponding field zone. Data suggested, for instance, an increase in the predictability of teams' tactical behaviours over the course of the match, independently of the phase of the game.

3.5 Wearable computing systems for feedback applications in sports

Björn Eskofier (University of Erlangen-Nürnberg, Germany)

Wearable computing systems play an increasingly important role in sports. They comprise of two parts. Firstly, sensors embedded into equipment are used for physiological (ECG, EMG, ...) and biomechanical (accelerometer, gyroscope, ...) data recording. Secondly, embedded microprocessors or wearable computers are used for the analysis of the recorded data. Together, these systems provide support, real-time feedback and coaching advice to sportsmen of all performance levels.

The talk focuses on four of the most prevalent challenges that have to be addressed in order to implement wearable computing systems: 1) integration: sensors and microprocessors have to be embedded unobtrusively and have to record a variety of signals 2) communication: sensors and microprocessors have to communicate in body-area-networks in a secure, safe and energy-saving manner 3) interpretation: physiological and biomechanical data have to be

interpreted using signal processing and pattern recognition methods 4) usability: interaction with the systems is provided by human-machine-interfaces (HMIs) that have to be intuitive and adapted to several use cases.

3.6 Science and Professional Coaching – still on hold

Sofia Fonseca (Lusófona University, Lisbon, Portugal)

Joint work of Fonseca, Sofia; Lopes, António

Following wise recommendation of Jäger and colleagues [1], the spatial organization of teams and players has been considered by various authors to study interaction behaviour in team sports, since players' distribution in the field is likely to mirror their individual and collective tactical options [2]-[4], and hence useful to characterize tactical performance. This approach has been generally accepted and it has been effectively embraced in recent studies [5]-[7], however, there is less consensus regarding the definition of the set of variables that are considered to describe interaction behaviour at different levels (team, player). Such variables, which can be viewed as individual and collective performance indicators, should be defined based on the game principles, tactical concepts and, ultimately, should represent a major source of information to high performance coaches, with whom a connection has not been yet fully established. Recent work on this topic was presented [8]-[10] in order to share and discuss ideas on this subject; and particularly to understand how relevant these could be on a practical context and which directions should be given to these so that this work can truly help and support professionals in high performance sports.

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3.7 Team Training Control in Cycling: Development and Application

Thomas Jaitner (TU Dortmund, Germany)

Due to the immense progress in information technologies and microelectronics during the recent years online monitoring of trainings parameters can be provided in many sports. To date, a main research focus in this area is on data acquisition and pre-processing by mobile devices with limited energy and computing resources as well as on communication infrastructure that even support remote analysis and feedback by distant experts within one training session. Less attention has been on how the huge amounts of sensor data can be processed and analysed to support or even autonomously control training.

This talk focuses on an example for an information technology based training optimization that has been developed to control team training in semi professional youth cycling. In group training, the power output depends on the position of the rider in the group. In slipstream it can be reduced up to 36% while reaching the same speed than on first position. Consequently, the cardiovascular and the metabolism load are reduced in rear positions (Neumann, 2000). For optimal group training, speed, formation, position of each cyclist within the group and the rotation sequence must be adapted to the individual performance potential of each athlete. The concept of the Team Training Control System including hardware components, software components and mathematical algorithms for training control as well as the results of the first experiments with different linear and non-linear control algorithms will be presented. Practical consequences for the application of the TCTS as well as the usability of the system are in main focus of the discussion.

3.8 Bridging the gap between computer science and practice in golf

Peter Lamb (TU München, Germany)

The sport of golf is one in which many coaches are open to using new technology. This situation presents an opportunity for computer science and practice to have a positive interaction. The current standard for golf swing analysis is based on comparing swing parameters of a client to a model of a correct swing, which is derived from a database of swing data taken from elite golfers. While this approach is well received by coaches and players, the logical next step is to develop an approach to look at adaptability in movement patterning. The majority of studies on human movement variability show us that no matter how skilled an athlete is, each movement is a response to the specific constraints affecting

the performance. Here was presented an approach to interacting with coaches on what the "correct" swing means, and ideas to use technology to incorporate findings from motor control and motor learning in the diagnostic package.

3.9 Computerized Game Observation in Goalball

Daniel Link (TU München, Germany)

Joint work of Link, Daniel; Weber, Christoph

Goalball is a Paralympic Sport for blind athletes. There are three players on each side who try to score by rolling the ball into the opposing net, past the defending team. Each player wears a blindfold so that each player is visually impaired equally. There are bells in the ball so that the players can echolocate it when it is moving. The current project has developed software, specifically for performance analysis in Goalball ("Goalscout" and "Goalview"). The software operates on tablet PCs for intuitive scouting to be efficient for the user. Furthermore, it generates positional data from the video frame which leads to precise information. The purposes of this project were to: a) design a prototype software, which can analyse performance efficiently and, b) analyse key aspects of Goalball.

From the Paralympic Games 2012 in London, all men's and women's games (17) from knockout matches were recorded and analysed with a prototype of the new developed software. Throwing patterns were characterized for various teams. For example, the Finnish and Brazilian Men's teams avoided throwing from Sector 9 (both just 2%). The Finnish team threw from the outer Sectors 73% instead of the middle sectors. The Brazilian team preferred to throw from Sectors 2, 5, 6 and 7. Goal-Sectors distributions were balanced, especially the Brazilian team. Finland tried to score on borderline sectors 3 and 4 and on outer sectors 8 and 9. General throwing patterns for individual teams should be used in forming a defensive strategy. Further research should investigate the underlying reasons for the observed throwing patterns. The developed software will allow such questions to be addressed.

3.10 Finding the I(nteraction) in TEAM

António Lopes (Lusófona University, Lisbon, Portugal)

Joint work of Fonseca, Sofia; Lopes, António; Baca, Arnold; Leser, Roland

In this talk, we presented a point of view about the relationship between professional coaching, computer scientists and sport scientists, bringing to discussion some key points on how the latter can interact in a high performance environment, and presenting an approach to build a Multilevel Sports Analysis Intelligence System (MSAIS) software.

The empathy for the different goals, particularly between sport scientists and coaches, seems to be the main gap for a fruitful joint work in high performance sports coaching. If professional coaches need to rely on meaningful data, they would need experts in the field to gather and process them to be easy to understand. These experts could be sports scientists

that have some of the expertise/education required to do this assessment. On the other hand, sport scientist need good quality data to better perform their expertise in this field, but these data are, most of the time, not accessible due to coaches and clubs' professional and legal issues. The successful cooperation between coaches and sport scientist lies in the answer, of the latter one, to the question: what can you do to help the coach to win? Although sport scientist cannot predict or prescribe the recipe to a successful season, they can effectively help to improve teams and coaches performance if they understand the high performance sports' environment, the game in depth and have something practical to add to the coaches goals. In our point of view, the first step is to feel empathy to the coaches profession (sacked if does not win) and the last step will be to submit high performance players to contextualized tests or task. Between these two steps, there is a lot of ground to cover, for instance gain coaches and teams trust and this can only be done by spending time in the club and, most of the times, just listening and observing. By getting deep knowledge of the surrounding environment, it will be easier to interact and communicate with the coaches and their empathy towards the sports scientist goals will develop until the sport scientist is recognized as team member.

There is not a known model suitable to engage all high performance sports' scenarios, but in the end, this interaction between coaches, sport and computer scientists in finding the right place and timing to develop their roles, is all a matter of trust. Moreover, trust needs to be built, as is a major part in the foundation of a successful interpersonal relationship. Another topic presented in this talk, was the Multilevel Sports Analysis Intelligence System (MSAIS) project that focus the interactive dynamics for visual analysis and its related issues. Coaches need to rely on meaningful and contextualized data, thus, automatic and fast assessment systems for tactical performance in team sports are today demands for any team. The validation of a new kind of assessment tool of tactical performance could provide the licensing of an innovative software system, one that could integrate an automatic live data collection and generate, in short real time, crucial information (i.e. pattern and error detection...) and reports for coaches to an online platform (see www.videobserver.com).

Finally, the talked ended with the announcement that a Portuguese Association Computer Science in Sport is established and this organization could work as an aid to bridge the gap between coaches, computer scientists and sport scientists by promoting their interaction in common activities.

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3.11 Automatically Creating a Computerized Expert for Live-Action Sports

Patrick Lucey (Disney Research, Pittsburgh, USA)

In February 2011, "Watson" (an IBM created AI computer system capable of answering questions) competed on Jeopardy! and comprehensively beat the best human players in the history of the quiz show. The technology of "Watson" evolved from IBM's "Deep

Thought" and "Deep Blue" projects in the 80's and 90's where they created a computer system which could beat the top human chess players. In sports, AI computer systems have been developed to automatically generate text summaries using match statistics (e.g. statsheet.com), although the reporting lacks tactical insight. Video games (e.g., EA Sports) have virtual commentators, which can describe and analyse what is going on in the match. Following this trend, we ask "why can't a computer system do similar things for real live-action sport?"

Enabling a computer to understand live-action sports is extremely difficult. Unlike chess and quiz shows, live-action sports have continuously changing variables with no guaranteed structure. Furthermore, whereas video games have the luxury of omnipotent knowledge about the virtual world, systems designed to understand the real world must be able to interpret noisy and missing sensor data (e.g. player and ball tracking). Like any other expert, the computer system needs to have seen an abundance of specific sports action to recognize patterns and explain why these are relevant and interesting. Obtaining exemplary data is an arduous task (i.e. capturing, sensing and annotating), and there are many technical challenges for real-time operation. Although challenging, the potential benefits of a computerized sports expert is enormous in both broadcasting and coaching domains. In this talk, I will first give an overview of the emerging field of sports-analytics and describe why such a system is a necessity. I will then talk about some of our recent work at Disney Research Pittsburgh in developing a computerized sports expert, specifically focussing on our work in: 1) automatically characterizing and recognizing team tactics in soccer, 2) Forming a representation of player tracking data which enables large-scale analysis of team behaviour and 3) automatically predicting shot-type and location of shots using Hawk-Eye tennis data.

3.12 Representing ball movement trends in football using an interactive visualization method

Stuart Morgan (Australian Institute of Sport, Australia)

Progress in computer science in areas such as machine learning, pattern detection and computer vision, is remarkably fast moving. Primary reasons for this are that problems are well defined, research groups have access to common data sets, and published papers frequently include source code and performance metrics that allow direct comparison to future approaches. Although some aspects of computer science in sport involve applications of existing solutions to new sport-related problems, there remain many areas in this field where novel solutions to technically difficult problems exist. For instance, understanding group behaviour in competitive and constrained tactical games is a difficult problem that is yet to find a satisfactory theoretical framework.

It is proposed that the computer science in sport community could address these challenges by increasing the efficiency of the international research effort. Common data sets and well-defined problems can accelerate progress in the understanding of performance in high performance sport. Also, providing open source solutions with novel published research allows other research groups to compound progress for the betterment of the entire computer science community. Therefore, it is proposed that an open source code base be established that incorporates novel and important work by international researchers in computer science

in sport, which is freely available to researchers subject to non-commercial Creative Commons license constraints. Further, rich, diverse and common data sets should be also made available to allow international research groups to compare, verify and accelerate the progress in computer science in high performance sport.

3.13 On winning the penalty shoot-out in soccer: Revisited

Tim McGarry (University of New Brunswick, Canada)

The penalty shoot-out is used to break tied games in the knock-out stages of soccer (football) competition. Its great importance in determining tournament outcomes is observed in the following descriptive statistics obtained from the 1976 European Championships through the 2010 FIFA World Cup. In 9 of 17 (53%) instances at least one of the two finalists won a penalty shoot-out earlier in that same competition, eight (47%) tournament winners won a penalty shoot-out, with three (18%) final games themselves being decided by penalty shoot-out. These statistics demonstrate that any team with design of winning a knock-out football tournament may well have to win a penalty shoot-out in pursuit of that aim. Thus, teams should prepare in advance for the reasonable likelihood of contesting a penalty shoot-out.

The shoot-out comprises of five alternating penalty kicks per team with each kick taken by a different pre-designated player from the available on-field players remaining at the final whistle. The highest tally of goals from five attempts each determines the winning team with equal tallies subsequently broken by "sudden death". In "sudden death" the next player per team is assigned a penalty kick in iterative fashion until a result is determined (i.e., one team scores and the other team misses on the same penalty kick pairing). Since each on-field player is awarded a single penalty kick, the line-up order in which penalty kicks are taken opens the possibility of optimized decision-making for influencing the final outcome. Using probability analysis and computer simulation, the following pre- and post-game strategies were identified. First, the best five penalty-takers should be assigned to the five penalty berths in reverse order, that is, the fifth best penalty-taker should take the first penalty kick, the fourth best penalty-taker the second penalty kick, and so on. In the event of sudden death, the sixth ranked penalty-taker should take the sixth penalty kick, the seventh ranked penalty-taker should take the seventh penalty kick, and so on. For this strategy to be used, the entire squad of players should be ranked a priori on their penalty-taking ability. The goalkeepers should likewise be ranked a priori on their penalty-stopping ability. These findings furthermore highlight possible consideration of tactical substitution of on-field players for higher ranked penalty takers, including higher ranked penalty stoppers (goalkeepers), in view of an impending penalty shoot-out.

These results are of practical importance in that they are shown to maximize the likelihood of winning a penalty shoot-out under certain initial conditions. Should the initial conditions change, then a different optimized line-up order would be expected, but the general underpinnings of identifying a priori an optimized line-up sequence, and the corresponding implications for effecting this optimized decision in sports practice by means of advance preparation, holds.

3.14 Process-oriented qualitative game analysis

Jürgen Perl (University of Mainz, Germany)

Joint work of Perl, Jürgen; Memmert, Daniel

Obviously, description and analysis of a complex game cannot be reduced to distributions of numbers but needs the dynamics of the playing processes. Therefore, success of a specific activity cannot be measured just by a ratio without setting it into relation to the situations in which it was used. The software-tool SOCCER, which has been developed in a cooperation of computer science and sport science, meets the demands by a combination of conventional data analysis, dynamic state-event-modelling and artificial neural networks: In particular, recognition of creative activities and simulation of their effectiveness in the con-text of game situations is of interest. However, different from normal process patterns, creative ones show two properties which make the net approach difficult: They fluctuate with time, and they are comparably seldom. In order to overcome those problems, a new type of network has been derived from the self-organizing network DyCoN, combining the learning dynamics with a fractal topologic dynamics: The basic structure of the TriTop approach (Triangular Topology) is a triangle of neurons, which by embedded new neurons iteratively is divided into three new triangles, causing the following effect: If adding new neurons with frequent information under the aspect of similarity, the corresponding starting triangles condense to clusters of refined ones. If adding a new neuron with rare information, which is not similar to any other, it stays isolated and therefore will be saved as a creative one.

3.15 Measuring Tactical Performance in Soccer

Jaime Sampaio (University of Trás-os-Montes, Vila Real, Portugal)

Joint work of Sampaio, Jaime; Goncalves, Bruno; Folgado, Hugo; Therón, Roberto

Our research team is exploring how soccer players' dynamic positional data can be used to assess tactical performance, by measuring movement patterns and inter- player coordination. The data is used to calculate overall, sectorial and position- specific centroids and, afterwards, the players' and dyads' distances, angles and coupling to these collective attractors is presented in co-variation with several situational variables (game location, game status, quality of opposition). Data analysis is processed with non-linear statistical procedures, such as approximate entropy, to identify the amount of randomness in each time series; and relative phase, to identify different modes of coordination (in-phase, anti-phase and transitions) during the matches dynamics. The results are be complemented with visual analysis tools to improve the understanding of emergent self-organization behaviours and the dynamic functional constraints at the scale of the environment.

3.16 Critical power models in endurance sports

Dietmar Saupe (University of Konstanz, Germany)

We develop methods for data acquisition, analysis, modelling, optimization and visualization of performance parameters in endurance sports with emphasis on competitive cycling. We use a differential GPS device (Leica GPS900) to extract high-precision trajectories of real cycling tracks. The equilibrium of the pedalling force Fped and resistance forces defines the relation between pedalling power Pped and cycling speed (P-v-model). The resistance forces are composed of the gravitational force, aerial drag, frictional losses in the wheel bearings, rolling resistance the inertial force as well as the slipstream force.

This model is implemented in our software that controls the brake force of a commercial Cyclus2 ergometer (RBM Elektronik). A prominent feature of our setup is that the Cyclus2 is controlled not via the standard TCP-IP interface, but via the RS232 interface, which allows us to control the torque of the eddy current brake and to measure the angular speed at a sampling rate with up to 40 Hz instead of only 2 Hz. Additionally, a cyclist and bicycle management, synchronized videos of the cycling tracks, an electronic gear shifter and the recording and visualization of various performance parameters during a ride are the main features cycling simulator. Furthermore, we use an SRM cycling power meter in conjunction with the Garmin Edge 800 bicycle computer to measure the performance parameters in the field. The model and the simulator setup have been validated by comparing outdoor speed and power measurements to model simulations as well as measurement on the simulator for real cycling tracks.

In order to optimize the pacing strategy for time trials of a specific cyclist on a specific bicycle and track, we use established physiological endurance models, such as the 3-parameter critical power model. Such models depict the endurance of a cyclist as a dynamical system and are often visualized as hydraulic models. Their major characteristics are a limited pedalling power contribution by the aerobic metabolism (critical Power Pc), a constrained anaerobic capacity Ea that an athlete can use to exceed the aerobic power for a limited time, as well as constraints on the maximum power Pm of the athlete, which is a function of the remaining anaerobic capacity.

The optimal pacing is defined as the pacing that ensures that the cyclist finishes the track in minimum time subject to the constraint that the physiological condition of the cyclist is always within an admissible range. Mathematically, this can be formulated as an optimum control problem, where the pedalling power is the control variable and the state variables are distance, speed and quantities that define the physiological state (ean). One major future goal of the Powerbike Project is to extend the physiological model to e.g. Morton's 3-component hydraulic model, and to improve its calibration in order to compute realistic optimal pacing strategies for cycling time trials, which are useful for athletes in practice. Moreover, an extension to a modelling of road cycling races with two or several cyclist using differential game theory is envisioned.

In the Dagstuhl presentation I will focus on the physiological modelling aspects, review the critical power concept, the measurement of the parameters, and some recent extensions that were proposed to generalize the model. It is an open issue, to what extent these models can be used to yield realistic optimal control solutions for time trial pacing strategies.

3.17 Effects of sensorimotoric insoles on gait pattern of adults

Wolfgang Schöllhorn (University of Mainz, Germany)

Joint work of Schöllhorn, Wolfgang; Eekhoff, Alexander; Hegen, Patrick

Traditionally, professional coaching is firstly oriented on archetypes of average world class athletes and secondly based on the assumption that an intervention does have the same, or at least, similar effects on all athletes. The identification of individual high performance athletes on the basis of time courses of kinematic and dynamic variables led to question traditional professional coaching. Furthermore, the identification of emotions or even of music which people were listening to during walking destabilized the classical point of view. The aim of the present investigation was to test the influence of active insoles as an example of intervention on the gait pattern of adults during the same and during different days.

Five male and five female subjects wore active insoles (Medreff) during walking over a force plat form and filmed by 8 Infrared cameras. Kinematic and dynamic data of 5 double step cycles were recorded on three days before, during, and after (situations) wearing active insoles. Four nonlinear (2x MLP, 2x SVM) and one nonlinear (cluster-analysis) pattern recognition approach were applied to all time courses of 3D-angles and angular velocities of the lower extremities during a single double step.

The results revealed individual recognition rates up to 100% for persons and for days by means of SVM. Situations (b, d, a) were recognised by rates of 87–95%. Again the dominance of individuality could be verified. Furthermore, short term influences of the insoles on gait patterns could be shown. Alltogether, the results question classical professional coaching and favor highly individual and situative training.

3.18 Game Analysis using the ISOPAR Method

Michael Stöckl (University of Vienna, Austria)

In game sports, single athletes or teams can be treated as complex dynamical systems. Thus, measurements of performance of athletes and teams are collective parameters which describe the outcome of the dynamical systems. In game sports the location where a performance takes place plays an important role, because the location already determines a certain amount of the constraints which influence and guide an athlete's or a team's performance. Therefore, the idea of the ISOPAR Method is to provide an opportunity to analyse performance with respect to the location where it occurred. Based on discrete measurements of performance, a continuous topology of performance is calculated across the field of play. The ISOPAR Method offers the opportunity to visually analyse sports performance using the ISOPAR maps which visualize such topologies of sports performance on a map of the pitch similar to the well- known isobar maps which illustrate barometric pressure. Such ISOPAR maps have already been used to analyse the performance of single shots of PGA Tour golfers and to identify difficulties at golf holes. Furthermore, the ISOPAR Method was used to study the performance of free kicks with respect to the respective outcome in women's soccer. ISOPAR maps were also used to investigate the play in field hockey and how it is influenced by the fact that there only is a right-handed stick in this sport.

3.19 Tactical performance assessment by measuring collective behaviour of football players

Anna Volossovitch (TU Lisbon, Portugal)

Players' positional data represents a relevant source of information. The spatial-temporal variables provide a consistent measure of team behaviour when considered simultaneously. However there are several questions concerning these variables: Could collective positional variables be used as measures of a quality of performance? How do players behave in successful and unsuccessful situations? Does collective behaviour change in function of players' expertise level? In our research the compound positional variables (team length, width, surface area and stretch index) were used to analyse the team performance in specific situation of match play and in a small-sided games. The results show that compound positional variables are able to reflect the variability of the offensive and defensive team behaviours of young players of different ages and expertise levels. Further research is needed to evaluate the potential generalization of these findings in order to understand better whether these compound variables can be considered as reliable performance indicators in monitoring of learning and performance during long-term soccer training.

3.20 Optimising Pacing Strategies for Team Pursuit Track Cycling

Markus Wagner (University of Adelaide, Australia)

Joint work of Wagner, Markus; Day, Jareth; Jordan, Diora; Kroeger, Trent; Neumann, Frank

Team pursuit track cycling is a bicycle racing sport held on velodromes and it is part of the Summer Olympics. It involves the use of strategies to minimize the overall time that a team of cyclists needs to complete a race. We present an optimisation framework for team pursuit track cycling and show how to evolve strategies using metaheuristics [1] for this interesting real-world problem. Our experimental results show that these heuristics lead to significantly better strategies than state-of-art strategies that are currently used by teams of cyclists.

References

1 M. Wagner, J. Day, D. Jordan, T. Kroeger, and F. Neumann, Evolving Pacing Strategies for Team Pursuit Track Cycling, in in Advances in Metaheuristics, Operations Research/-Computer Science Interfaces Series, Springer, 2013.

3.21 Computer Science in Sport at the University in Magdeburg, Germany

Kerstin Witte (University of Magdeburg, Germany)

The purpose of this short presentation is the introduction of the several fields of computer science in sport in our department with applications. Especially, I talk about following topics (1) Development and Optimization of Sport Equipment by Integration of Measuring and Information Systems, (2) Possibilities for determination of anticipation under laboratory and field conditions (software, video presentation, virtual reality, recording of interaction by motion capturing), (3) Match analysis in Combat Sport, (3) Modelling (biomechanical modelling, using nonlinear approach for technique analysis and performance analysis).

4 Working Groups

The Dagstuhl Seminar on "Computer Science in High Performance Sport – Applications and Implications for Professional Coaching" had a mixed groups of presentations during the three days. The overview of each session is presented next.

4.1 Day 1, Session 1

Speakers: Jürgen Perl, Sofia Fonseca, Ricardo Duarte, António Lopes, Michael Stöckl
Chair: Jaime Sampaio

Jürgen Perl was the first presenter to discuss his work on process oriented qualitative game analysis for football for which he introduced the software SOCCER. This software combines the conventional data analysis with dynamic state-event-modelling and artificial neural networks for the recognition of creative activities and their effectiveness in the context of the game. To overcome the difficulty to detect patterns stemming from rare events such as creative activities he presented TriTop, which is a type of network that derived from DyCoN, combining the learning dynamics with a fractal topologic dynamics that allows to isolate the neurons that carry information about rare events and that can be saved as creative ones.

Following, Sofia Fonseca provided a talk on the use of spatial metrics to characterize tactical organization and reminded that there still is a lack of scientific knowledge on the set of variables that can be used to assess team sports performance. She stated that those variables should be defined on well-known game principles and tactical concepts thereby effectively representing the source of information to high performance coaches. She also pointed out the limitations of some commonly cited spatial metrics variables (surface area, stretch index, team width, team length) and the outstanding characteristics of the Voronoi diagrams approach and related variables recently used in the literature.

Next, Ricardo Duarte gave a communication that showed different studies under development to capture individual and team tactical behaviours in soccer in order to analyse the interpersonal coordination tendencies. These sets of studies are trying to gather useful information by the transformation of the position data of players using variables such: player-to-locus distance, dominant region, and the number of intra- and inter-team local

spatial interactions to determine player profiles according to their playing positions and compound positional variables such as surface area, stretch index, team width, team length, contraction-expansion speed and collective velocity to capture team characteristics. Regarding individual tactical behaviour he stated that player-to-locus distance, the individual dominant regional areas and the number of intra- and inter-team local spatial interactions had exhibited important differences between playing positions. Considering the collective tactical behaviour, preliminary results indicate an increase in the regularity of the teams' tactical behaviours over the course of the match, independently of the phase of the game.

The fourth presentation was made by António Lopes and was titled Finding the I(nteraction) in TEAM. This presentation looked upon the communication and interaction process between professional coaches, computer and sport scientists from different point of views. This first issue gave rise to a discussion on how sport and computers scientist should interact with professional coaches and on the importance of understanding the different goals, roles and tasks that everyone has in order to improve this fruitfully synergic collaboration. The second matter presented was the Multilevel Sports Analysis Intelligence System project that focuses on the interactive dynamics for visual analysis and its related issues and characteristics to provide meaningful, contextualized and easy to understand data. This talked ended with the announcement that a Portuguese Association Computer Science in Sport is established and this organization could work as an aid to bridge the gap between coaches, computer scientists and sport scientists by promoting their interaction in common activities.

The last presentation of the morning was made by Michael Stöckl and he talked about the application of the ISOPAR method in game analysis of golf, free kicks in soccer, field hockey, and tennis. This method allows the analysis of performance with respect to the location where it occurred. This method consists in the creation of a continuous topography of performance based on discrete measurements that is calculated across the playing field. This method differs from the heat maps as it has the possibility to weight values.

4.2 Day 1, Session 2

Speakers: Martin Lames, Björn Eskofier, Wolfgang Schöllhorn, Michael Brink, Aaron Coutts, Chikara Miyaji
Chair: Stuart Morgan

Martin Lames was the first presenter of this section, with a presentation entitled Theory and practice of computer scientist intervening in practice, where he started to talk about the different types of knowledge: theoretical and applied. To make his point he developed a pie chart for the various concepts of science and sport, followed by the distinct type of research that can is being done in sports science: basic, applied and for evaluation. This allowed the participants to have a picture and to discuss about the different purposes that can drive the goals of a sport scientist (from a practical side into scientific problem or vice-versa) and to gain insight about epistemological concepts and models.

Björn Eskofier made the following presentation about wearable computing systems for feedback applications in sports. He introduced the team that works with him and showed how wearable computing systems are divided in physiological and biomechanical data recording devices whose embedded microprocessors allow to analyse the collected data. He described the four of the most prevalent challenges that have to be addressed in order to implement wearable computing systems: (1) microprocessors must be embedded unobtrusively with the

ability to record a variety of signals; (2) microprocessors have to be able to communicate in body-areas' networks in a sustainable manner; (3) the recorded data have to be interpreted using signal processing and pattern recognition methods and (4) the interaction with the systems has to be intuitive and adapted to several use cases. He showed some examples of hardware (Shimmer sensor platform) and the application for golf, MoGoPuCo. There were some questions in the discussion about the accuracy demands and about the training and competition gap.

Next, Wolfgang Schöllhorn gave a presentation on pattern recognition of movements and the impact of insoles to gait. He started by questioning the traditional coaching methods that are based on the assumption that an intervention has a similar effect on all athletes. He presented his research work that aimed to test the influence of active insoles on the gait pattern of adults during the same and during different days. For this, five male and five female subjects wore active insoles (Medreff) while walking over a force platform and were filmed by eight infrared cameras. Four nonlinear and one nonlinear analysis for pattern recognition were applied to all recorded data (before, during, and after wearing active insoles). His results revealed dominance of individuality verified by individual recognition rates up to 100% for persons and for days, by means of SVM. The presentation was wrapped-up by questioning the classical professional coaching that, unlike his research results show, do not take into consideration individual training.

The following presenter was Michael Brink who discussed a framework for the monitoring of physical and psychological load and recovery. His talk pointed out models of external and internal load and recovery giving rise to questions about their operationalization and the complexity of the system construct for the recovery, which depends on the measures of recovery (subjective and/or objective), on the system, the level, and the course.

Aaron Coutts then presented a theoretical working model for implementing a training monitoring system in a professional football club. He started by referring the main challenge of scientists working with professional team sports, namely being able to individualize training in order to meet the needs of both the individual and team, as players have different roles, recovery rates, experience, etc. So care is needed when monitoring and controlling training tasks in order to improve performance and to avoid overreaching (prevent injury) in players. This justifies the need to have systems that accurately assess players coping with training. Logistical issues and present practical models of data analysis were discussed and supported by examples of Australian football coaches in order to provide accurate decision-making and fast feedback.

Finally, Chikara Miyaji presented the SMART video database that appears motivated by the absence of specific media focused on sports movement. The idea is that this database should be an easy way to search in recorded shared videos, as a user, in first instance, will access the information based on the behavior of previous users, sorting what is important from non-important data. He presented his vision and an all-in-one camera prototype that will enable users to record, upload and store video data.

4.3 Day 2, Session 3

Speakers: Wouter Frencken, Jaime Sampaio, Anna Volossovich, Stuart Morgan, Daniel Link
Chair: Koen Lemmink

Wouter Frenken started this session. He mentioned the importance of a sport scientist to be close to the teams with whom he works as this proximity will improve the chances of

him being recognized as a team member and consequently being integrated and included in the activities in the club. Following the topic of the present seminar, he has explained, also based on his experience, that the communication between sport scientists and coaches is essential to guarantee that the former understand the needs of the latter. Wouter has presented the INMOTIO software, which he is developing in his research, but pointed out that there is a mismatch between the outcomes of the software and the specificity of the coaches' requirements. The software is useful for scientific research, and the scientific issues that are in the table, but needs to be adjusted to respond to what coaches are interested in extracting from the game.

Next, Jaime Sampaio presented some of his studies, which aim to explore how soccer players' dynamic positional data can be used to assess tactical performance, by measuring movement patterns and inter-player coordination. He considers the teams' centroid positions as a collective attractor and studies how this relates with other measures, such as angles and distances, as well as situational variables (e.g., game location, game status, quality of opposition). Data is analysed by means of non-linear methods (entropy and relative phase), supported by visual analysis tools.

Following this, Anna Volossovitch presented her exploratory work on using various spatial metrics to assess performance in sports games and to identify behavioral patterns. She considered the teams' lengths, widths, surface areas and stretch indexes in specific situations of a match play in a small-sided game of soccer, played by young players of different ages and expertise levels. According to the obtained results, these variables reflect the variability of the offensive and defensive team behaviours. However, it is still not clear how these variables can effectively be used as performance indicators.

Stuart Morgan has gave his presentation on representing ball movement trends in football. The analysis is performed using a visualization technique based on the ISOPAR method previous presented by Michael Stöckl. During his presentation, he stated the current trend and importance to develop such systems for independent data exploration in an open source fashion. He showed a demo of an interactive tool called 3D View Kit and shared his vision of an Open Performance Analysis system and to find a community of practice. Some key points followed the discussion over incentives to people participation and requirements specifications for the system.

Daniel Link presented his research project that aimed to design prototype software that could be used to analyse key aspects of Goalball, which is a Paralympic Sport for blind athletes. This specific software, "Goalscout" and "Goalview", intends to be very intuitive and efficient for the user. The match statistics that one can obtain are throw techniques, throws and sectors (target – throws). Results from an application at the Paralympic Games 2012 in London, allowed the identification of throwing patterns for various teams which can be considered by coaches for forming defensive strategies. Still, further research is needed to improve this tool regarding the improvement of detection technique since it has some restrictions concerning throwing positions.

4.4 Day 2, Session 4

Speakers: Markus Wagner, Thomas Jaitner, Peter Lamb, Tim McGarry
Chair: Dietmar Saupe

The first speaker, Markus Wagner, presented a talk on Evolving Pacing Strategies for Team Pursuit Track Cycling. The aim of this work is to optimize pacing strategy by minimizing

the overall time that a team of cyclists needs to complete a race. Wagner presented a novel application of metaheuristics to the optimisation of elite competitive track cycling, in which they have used a state-of-the-art evolutionary algorithm as a local optimiser for the power profiles called Covariance Matrix Adaptation Evolution Strategy (CMA-ES). Wagner's algorithm has led to better strategies than those described in the literature, and therefore have potential to aid athletes in improving their performance.

Next, Thomas Jaitner has addressed an issue that emerges from an online monitoring of training, which is a common practice in various sports these days. Namely, he has investigated how the huge amounts of sensor data can be processed and analysed to support or even autonomously control training, particularly in semi professional youth cycling. The individual training impulse in a group training depends on the position of the rider. The front rider has higher cardiovascular and metabolic demands in comparison with those in rear positions. Thus, for optimal group training, speed, formation, position of each cyclist within the group and the rotation sequence must be adapted to the individual performance potential of each athlete. Thomas has presented a Team Training Control System (TCTS) concept and has discussed the practical consequences for the application of the TCTS as well as its usability.

Peter Lamb has presented his work on technique analysis and coach interaction in golf, where some acoustic feedback is given to players as they prepare to shoot. He started by making an overview of the current standard for golf swing analysis. He pinpointed a possible next step by the development an approach that looks up to adaptability in movement patterning, in the response to specific constraints. His approach is based on the use of biomechanical characteristics of the swing that are captured by the sensors, which incorporate findings from motor control and motor learning into a "diagnostic package" to improve coaches' feedback.

Tim McGarry was the last speaker of this session, and he revisited one of his research topics, namely on winning the penalty shoot-out in soccer (football). The goal of this work was to present a model for selecting the appropriate line-up for the penalty shoot, as well as for a sudden-death event, given that any team to win a knock-out football tournament may well have to win a penalty shoot-out in pursuit of that aim. Hence, teams should prepare in advance for the reasonable likelihood of contesting a penalty shoot-out. In what is suggested by Tim, players and goalkeepers should be ranked a priori on their penalty-taking ability and penalty-stopping ability, respectively. Once these are ranked, and according to Tim's results on probability analysis and computer simulations, the suggested strategies are: First, the best five penalty-takers should be assigned to the five penalty berths in reverse order, that is, the fifth best penalty-taker should take the first penalty kick, the fourth best penalty-taker the second penalty kick, and so on. In the event of sudden death, the sixth ranked penalty-taker should take the sixth penalty kick, the seventh ranked penalty-taker should take the seventh penalty kick, and so on. As discussed in the end of this talk, there are a number of conditions that may change and influence the players initial ranking order (e.g., stress, injury during the game), however, and according to Tim's findings, the general underpinnings of identifying a priori an optimized line-up sequence, and the corresponding implications for effecting this optimized decision in sports practice by means of advance preparation, holds.

4.5 Day 3, Session 5

Speakers: Patrick Lucey, Josef Wiemeyer, Thorsten Stein, Arnold Baca, Kerstin Witte, Martin Lames
Chair: Martin Lames

This was the last session of the seminar. The first presentation was Patrick Lucey's introduction of large scale analysis of continuous sport using player roles. He started by giving an outline of the emerging field of sports analytics, describing the need of this field. Then he gave an overview of the recent work in the development of a computerized sports expert at Disney Research Pittsburgh (for ESPN), by focusing on three lines of R&D: (1) the automatic recognition of team tactics in soccer, (2) the representation of player tracking data and (3) the automatic prediction of shot-type and its location using Hawk-Eye tennis data. During the talk, he focused on the difficulty to generate automatic reports that contain tactical information, because a real live-action sport has continuously changing variables with no guaranteed structure, due to context interpretation (dynamic role and identity of players' representation, noise, missing data or flaws, etc..). Thus, computers will "struggle to understand" these dynamic structures, needing an abundance of data to be able to recognize and interpret patterns that are relevant in order to predict and produce automatic content. There is a need to work close with coaches to generate meaningful labels and problem definitions in order develop models that can assign role and identity representation (i.e. shape context, heat maps). He evidenced the potential benefits of a computerized sports expert in broadcasting domain by enabling the interaction of the audience in the game.

Josef Wiemeyer gave a talk about Serious Games presenting his recent research results on game experience for learning and training in sport. He started by presenting a four lens model framework to study the topic. He discussed the role serious games can play in health promotion (i.e. Nintendo Wii, Playstation Move) and discussed the relative transfer of skills from games to real life sport, as they can contribute to improve a number physical, social and psychological competencies. He showed some examples of good practice and the contribution to build personal learning environments. Still, the question remains: is there an effective transfer from virtual worlds to real world? The discussion followed with the suggestion of combining both virtual and real worlds as an approach to study serious games activities (i.e., augmented reality). He ended presentation promoting GameDays 2014 – 4th International Conference on Serious Games from April 1st to 4th at TU Darmstadt, Germany.

Following, Thorsten Stein presented the current and future research of robotics and motor learning. He gave an overview of how robotics can be used to investigate human motor adaptation and skill learning. He started to talk about the classic experimental design of motor adaptation experiments and the underlying theoretical considerations and gave a brief overview of current research topics and findings in the field of motor adaptation. Robot devices have been used to study motor adaptation tasks but also can be used for research in skill acquisition in sports. He evidenced some challenges regarding the use of robots in sports tasks like the upper limb movements that occur in 3D space and the forces that differ from those used in motor adaptation experiments; and that the relationship between motor adaptation and skill learning in sports is far from clear. Afterwards he talked about robotic guidance in motor learning (kinematic aspects of robotic guidance and dynamic aspects of robotic guidance) by presenting new developments in robotic devices, which can be used in the research of skill learning in natural movement tasks. Ideas on how the existing experimental designs need to be enhanced to be able to investigate skill learning with robotic devices were also a subject of discussion in his talk.

Arnold Baca made a presentation about his ongoing project on Intelligent Systems. The work consists in joint projects of wearable technologies (wireless sensors on athletes' sports equipment) and the use of positional data in order to develop mobile coaching (e-coaching) to aid athletes and coaches to support their training sessions. The idea consists in giving feedback in real time through the analysis of the performance data that is collected continuously, like the physical activity loads. This way coaches can guide training remotely and give real time assessment to athletes by smart phone application via ANT+^{TM}. He presented two examples, one on strength in rowing and another on running a marathon using mobile coaching. The interest in such kind of tools have led to the development of sub-modules into a server application to integrate intelligent algorithms processing collected data in order to automatic generate feedback instructions (i.e., load-based performance development using the antagonistic meta-model PerPot).

The discussion on this topic revealed the need to build a joint database of positional data for benchmarking in the sport science community in order to improve models for performance optimization and advanced data processing. At the end an announcement for the Conference of the German Association of Computer Science in Sport (dvs-Sektion Sportinformatik), from September 10^{th} to 12^{th}, 2014, Vienna, Austria, was made.

Following, Kerstin Witte presented the projects in the University of Madgeburg research center: (1) development and optimization of sport equipment by integration of measuring and information systems, (2) possibilities for determination of anticipation under laboratory and field conditions, (3) match analysis in combat sport and (4) modelling (biomechanical modelling for technique analysis and performance analysis).

Martin Lames, as one of the organizers and the new president of IACSS, closed this session and the seminar. He presented the IACSS and the next IACSS symposium on Darwin, Australia, from 22^{th} to 24^{th} of June 2014 and issues were discussed. The strategic need to develop a US representation and to attend the MIT conference was recognized. Another subject of discussion was education on computer science in sport and suggestions were made on organizing pre-conference workshops and on writing papers for IJCSS. The participants have agreed to build a data repository in order facilitate the collaboration between different institutions with common and complementary research topics or framework, and to apply a survey to study attitude and usage of ICT in (elite) sports. Finally, the organizing committee announced the organizers for the proposal for a possible follow up Dagstuhl seminar on computer science and sport.

Participants

- Arnold Baca
Universität Wien, AT
- Michel S. Brink
University of Groningen, NL
- Aaron Coutts
University of Technology – Sydney, AU
- Ricardo Duarte
TU Lisboa, PT
- Björn Eskofier
Univ. Erlangen-Nürnberg, DE
- Sofia Fonseca
University Lusófona – Lisboa, PT
- Wouter Frencken
University of Groningen, NL
- Thomas Jaitner
TU Dortmund, DE
- Peter Lamb
TU München, DE
- Martin Lames
TU München, DE
- Koen A.P.M. Lemmink
University of Groningen, NL
- Daniel Link
TU München, DE
- António Lopes
University Lusófona – Lisboa, PT
- Patrick Lucey
Disney Research – Pittsburgh, US
- Tim McGarry
University of New Brunswick, CA
- Chikara Miyaji
Japan Institute of Sports Science – Tokyo, JP
- Stuart Morgan
Australian Institute of Sport – Bruce, AU
- Jürgen Perl
Mainz, DE
- Jaime Sampaio
Universidade de Trás-os-Montes – Vila Real, PT
- Dietmar Saupe
Universität Konstanz, DE
- Wolfgang Schöllhorn
Universität Mainz, DE
- Thorsten Stein
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- Michael Stöckl
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- Anna Volossovitch
TU Lisboa, PT
- Markus Wagner
University of Adelaide, AU
- Josef Wiemeyer
TU Darmstadt, DE
- Kerstin Witte
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Report from Dagstuhl Seminar 13311

Duality in Computer Science

Edited by

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Abstract

Duality allows one to move between the two worlds: the world of certain algebras of properties and a spacial world of individuals, thereby leading to a change of perspective that may, and often does, lead to new insights. Dualities have given rise to active research in a number of areas of theoretical computer science. Dagstuhl Seminar 13311 "Duality in Computer Science" was held to stimulate research in this area. This report collects the ideas that were presented and discussed during the course of the seminar.

Seminar 29. July to 02. August, 2013 – www.dagstuhl.de/13311
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1 Executive Summary

Mai Gehrke
Jean-Eric Pin
Victor Selivanov
Dieter Spreen

This seminar concentrated on applications of duality in computation, semantics, and formal languages.

Duality and computation

Consider the area of exact real number computation. Real numbers are abstract infinite objects. Computing machines, on the other hand, can only transform finite objects. However, each real number is uniquely determined by the collection of rational open intervals that contain it, or a certain sub-collection thereof. Rational intervals can be finitely described as a pair of rationals. So, in order to compute with real numbers one has to compute with certain

properties, i.e., one no longer works in the space of the reals but in the algebra generated by these properties. In doing so, the open intervals are considered as first-class objects and the concept of point is taken as a derived one. This is exactly the approach of pointless topology which tries to develop analytical concepts in a pointfree way, hereby using constructive logic.

Duality and semantics

In logic, dualities have been used for relating syntactic and semantic approaches. Stone's original result is in fact of this type as it shows that clopen subsets of Stone spaces provide complete semantics for classical propositional logic. This base case has been generalized in various directions. There is a general scheme underlying this work: given a logic, construct its Lindenbaum algebra which in these cases is a Boolean algebra with unary operators. Jonsson-Tarski duality relates such algebras to binary relational structures which in the modal case are just Kripke frames. In this setting, a wide spectrum of duality tools are available, e.g. for building finite models, for obtaining interpolation results, for deciding logical equivalence and other issues. For infinitary logics, Stone-type dualities have also played an important role starting with Scott's groundbreaking first model of the lambda-calculus which is a Stone space. Subsequently Abramsky, Zhang and Vickers developed a propositional program logic, the logic of finite observations. More recently work of Jung, Moshier, and others has evolved this link between infinitary and finitary logics in the setting of logics for computation much further.

Duality and formal languages

The connection between profinite words and Stone spaces was already discovered by Almeida, but Pippenger was the first to formulate it in terms of Stone duality. Gehrke, Pin and Grigorieff lately systematized and extensively developed this discovery which led to new research efforts in formal language theory. A final goal is a general theory of recognition.

The seminar brought together researchers from mathematics, logic and theoretical computer science that share an interest in the fields of computing with infinite data, semantics and formal languages, and/or the application of duality results. The researchers came from 12, mostly European, countries, but also from Argentina, Japan, Russia, South Africa, and the United States.

Some of the specific questions that were investigated in talks and discussions:

- Explore the use of the link between finitary and infinitary Stone dualities in other settings than semantics;
- Explore the link between complexity theory and semantics provided by the connection via duality theory;
- Identify the relationship between game semantics and dual spaces;
- Explore the link between the profinite semi-groups used in formal language theory and logics given by state-based transition systems or categorical models)

2 Table of Contents

3 Overview of Talks

3.1 Factoriality and the Pin-Reutenauer procedure

Jorge Almeida (University of Porto, PT)

The problem of separation of two rational languages by a language of a special type becomes a classical topological separation problem in the associated profinite completion of the free semigroup on the underlying alphabet. From an algorithmic viewpoint, it is better to work with an intermediate free algebra provided it is sufficiently rich to capture non-emptiness of the intersection of the closures of two rational languages. The natural signatures to consider for such algebraic structures are "implicit" in the sense that semigroup homomorphisms between finite semigroups remain homomorphisms in the enriched signature.

We consider implicit signatures on finite semigroups determined by sets of pseudonatural numbers. We prove that, under relatively simple hypotheses on a pseudovariety V of semigroups, a finitely generated free algebra for the largest such signature is closed under taking factors within the free pro-V semigroup on the same set of generators. We also show that the natural analogue of the Pin-Reutenauer descriptive procedure for the closure of a rational language in the free group with respect to the profinite topology holds for the pseudovariety of all finite semigroups. As an application, we show that the Pin-Reutenauer procedure holds for a pseudovariety of semigroups with respect to the signature consisting of multiplication and pseudo-inversion if and only if the pseudovariety is full with respect to this signature.

3.2 The Sierpinski space as a higher inductive type

Andrej Bauer (University of Ljubljana, SI)

The Sierpinski space, which has two points one of which is open, is the dualizing object for duality between spaces and frames. The distributive lattice structure of Sierpinski space can be axiomatized in lambda calculus, which leads to a connection between topology on one side and logic and computation on the other. This fruitful connection has been used in the past to give logical characterizations of various topological properties, as well as to explain how we can directly compute with topological spaces.

We can ask whether the Sierpinski space can be constructed in type theory. Traditionally this is done with the use of the termination monad or a suitable co-inductive type. But in homotopy type theory we can construct the Sierpinski space as a higher inductive type, which leads to some new possibilities.

3.3 On normal numbers (including new results)

Veronica Becher (University of Buenos Aires, AR)

Joint work of Becher, Veronica; Bugeaud, Yann; Carton, Olivier; Heiber, Pablo; Slaman, Theodore
Main reference V. Becher, P. A. Heiber, T. A. Slaman, "A polynomial-time algorithm for computing absolutely normal numbers," Information and Computation, Vol. 232, Nov. 2013, pp. 1–9, 2013.
URL http://dx.doi.org/10.1016/j.ic.2013.08.013
URL http://www.dc.uba.ar/people/profesores/becher/normal_dagstuhl.pdf

This is a summary of recent result on normal numbers obtained by combining algorithmic, combinatorial and number-theoretic tools.

- Normality to different bases. Joint work by Becher and Slaman, 2013. We show that the discrepancy functions for different bases for which a real number can be normal are pairwise independent. As an application we answer two open questions. One is that the set of real numbers which are normal to at least one base is properly at the fourth level of the Borel hierarchy. The other is to show that that if R and S are a partition of bases closed under multiplicative dependence, then there are real numbers that are normal to each base in R and not simply normal to any base in S.
- On Simple normality Joint work by Becher, Bugeaud and Slaman, 2013. We give the conditions on a subset of positive integers such that there exists a real number that is simply normal to all the elements in the set and not simply normal to none of the element in it complement.
- A polynomial time algorithm for computing normal numbers Joint work by Becher, Heiber and Slaman, 2013. Using combinatorial and basic measure theoretic arguments we obtain al algorithm that computes an absolutely normal number with just above quadratic time complexity. We actually computed an instance.
- Normality and Automata. Joint work by Becher, Carton, Heiber, 2013 We extend the theorem that establishes that a real number is normal to a given base if, and only if, its expansion in that base is incompressible by lossless finite-state compressors, a particular class of finite-state automata. We show that the incompressibility results also hold for non-deterministic automata even if they are augmented by counters.

3.4 A coinductive approach to computable analysis

Ulrich Berger (Swansea University, UK)

We describe continuous real functions by a quantifier free coinductive predicate and show that from a proof of a function f having this property one can extract a memoized implementation of f that operates on real numbers in signed digit representation.

We will show that this is an example of a general approach to computation where one replaces operations on (constructive representations of) mathematical objects by constructive proofs of properties of these objects.

Technically, this approach is based on a realizability interpretation of Church's Simple Theory of Types.

3.5 The Unreasonable Effectiveness of Choice or Metamathematics in the Weihrauch Lattice

Vasco Brattka (Universität der Bundeswehr – München, DE)

URL http://arxiv.org/find/all/1/au:+Brattka_V/0/1/0/all/0/1

The concept of Weihrauch reducibility captures the idea of reducing one problem computationally (or continuously) to another problem. Formally, the reducibility yields a lattice with a rich algebraic structure that has some similarities to the resource oriented interpretation of linear logic. This lattice can be seen as a refinement of the Borel hierarchy for multi-valued functions and it can be used to classify the computational content of mathematical theorems. In this approach for all-exists theorems are just interpreted as multi-valued functions and positioned in the Weihrauch lattice. If Theorem A can be reduced to Theorem B in this lattice, then this means that the input and output data of these theorems can be computably (or continuously) transferred into each other such that a reduction of A to B is obtained. Over the previous 5 year a large number of theorems have been classified in this way by several authors and interesting separation techniques have been developed along the way. A particular role is played by so-called choice principles, which can be used to calibrate not only a large class of theorems, but also several natural classes of functions. The aim of this talk is to present a survey on the classification of theorems in the Weihrauch lattice with some outlook on recent results.

3.6 Complete quasi-metric spaces in computer science, logic, and algebra

Matthew de Brecht (NICT – Osaka, JP)

We will present our research on the descriptive set theory of quasi-Polish spaces, which are defined as the countably based topological spaces which admit a Smyth-complete quasi-metric. Quasi-Polish spaces are a natural generalization of Polish spaces to include important classes of non-metrizable spaces while retaining a rich descriptive set theory. Most countably based spaces in computer science, including omega-continuous domains, are quasi-Polish. From the locale theoretic perspective, quasi-Polish spaces correspond to the locales with a countable presentation in terms of generators and relations. All countably based spectral spaces are quasi-Polish, which suggests the relevance of quasi-Polish spaces to the field of commutative algebra.

3.7 Reverse Reverse Mathematics

Hannes Diener (University of Siegen, DE)

Topological—or more general Heyting-valued—models have been a useful tool to provide counterexamples to various principles in constructive mathematics. In particular, topological models can be used to separate principles that have been investigated in the program of constructive reverse mathematics. The goal of (constructive) reverse mathematics is not to ask what principles are sufficient to prove theorems (normal "forward" mathematics) but also what principles are necessary to prove them.

In this talk we will present some work (very much) in progress that could be labeled "reverse reverse mathematics": namely, we will ask the question what properties the space underlying a topological model needs to satisfy in order to be able to separate between certain principles.

3.8 Ramsey theory and Gelfand duality

Willem Fouché (University of South Africa, ZA)

We discuss non-archimedean groups which are extremely amenable and the role that Ramsey theory plays in identifying these extremely amenable groups. We indicate how Gelfand duality can be used to lead to a better understanding of the constructive content of the topological versions of structural Ramsey theory. For further background:

References

1 W. L. Fouché: "Algorithmic Randomness and Ramsey Properties of Countable Homogeneous Structures. L. Ong and R. de Queiroz (Eds.): WoLLIC 2012, LNCS 7456, pp. 246–256, 2012. Springer-Verlag Berlin Heidelberg.
2 W. L. Foucheé. "Martin-Löf randomness, invariant measures and countable homogeneous structures." Theory of Computing Systems, 52:65–79, 2013.

3.9 Boolean topological algebras as dual spaces

Mai Gehrke (University Paris-Diderot, FR)

Joint work of Gehrke, Mai; Grigorieff, Serge; Pin, Jean-Eric
Main reference M. Gehrke, "Stone Duality, Topological Algebra, and Recognition," HAL-00859717, version 2, 2013.
URL http://hal.archives-ouvertes.fr/hal-00859717

Based on Stone Priestley duality for additional operations on lattices, one can show that topological algebras based on Boolean spaces are the dual spaces of certain Boolean Algebras with additional Operations (BAO). In the special case of the profinite completion of an abstract algebra the dual BAO is always the BA of recognizable subset equipped with the residuals of the lifted operations of the original algebra. This result, as well as duality

between sublattices and quotient spaces are the main duality theoretic results behing our joint work with Serge Grigorieff and Jean-Eric Pin generalising various elements of the theory of regular languages.

3.10 Duality for sheaves of distributive-lattice-ordered algebras over stably compact spaces

Sam Van Gool (Radboud University Nijmegen, NL)

A sheaf representation of a universal algebra A over a topological space Y can be viewed as a special subdirect product decomposition of A indexed by Y. Indeed, in case Y is a Boolean space, sheaf representations of A correspond exactly to weak Boolean product decompositions of A. Moreover, if A is a distributive lattice, then Boolean sheaf representations of A correspond to decompositions of the (Stone-Priestley) dual space of A into a Boolean sum, i.e., a disjoint sum indexed over the underlying Boolean space satisfying a certain patching property for the topology on the sum.

We study sheaf representations of distributive lattices over stably compact spaces, which are the natural T_0 spaces associated to compact ordered spaces. In particular, the class of stably compact spaces contains both the class of compact Hausdorff spaces and the class of spectral spaces. We introduce an appropriate condition on sheaves, that we call fitted, which allows us to prove the following:

Theorem. Fitted sheaf representations of a distributive lattice A over a stably compact space Y are in one-to-one correspondence with patching decompositions of the Stone-Priestley dual space of A over the space Y.

Here, a patching decomposition of a topological space X over a space Y is most conveniently described by a continuous map from X to Y which satisfies a certain patching property, reflecting the patching property of the sheaf. If the indexing space Y is Boolean, then such a patching decomposition precisely corresponds to a Boolean sum. However, since stably compact spaces may have a non-trivial specialization order, the correct notion of patching decomposition is no longer a disjoint sum of spaces, but rather corresponds to an ordered sum with an appropriate topological property.

In our recent joint work with V. Marra [1], we showed that sheaf representations of MV-algebras can be obtained via decompositions of the Stone-Priestley dual spaces of their distributive lattice reducts. Thus, the results described here show in particular that the methods employed in [1] are an instance of a more general phenomenon, and open the way for studying sheaf representations of other varieties of distributive-lattice-ordered algebras via decompositions of their dual spaces, which may be indexed over any stably compact space.

References

1 M. Gehrke, S. J. van Gool, and V. Marra, *Sheaf representations of MV-algebras and lattice-ordered abelian groups via duality*, (2013), submitted, preprint available at arXiv:1306.2839.

3.11 Approximation spaces (spaces of Choquet Games), à la domain approach to quasi-Polish spacesy

Serge Grigorieff, (University Paris-Diderot, FR)

Quasi-Polish spaces generalize both Polish spaces and countably based continuous domains. They can be seen as the analog of Polish spaces when Hausdorff T_2 separation axiom is replaced by Kolmogorov T_0 axiom. In a fundamental recent paper, Matthew de Brecht showed that a large part of the theory of Polish spaces admits a counterpart with quasi-Polish spaces.

We introduce another class of topological spaces, extending that of quasi-Polish spaces: approximation spaces. The definition is based on an approximation relation which formalizes a "strong containment relation" between basic open sets such that strongly decreasing chains have a non empty intersection.

An example of an approximation relation is obtained by lifting to basic open sets the way-below (or approximation) relation in a continuous dcpo.

The subclass of convergent approximation spaces is obtained by requiring that every strongly decreasing chain is a fundamental system of neighborhoods of some point.

We prove that quasi-Polish spaces are exactly the T_0 second-countable convergent approximation spaces. This gives an "à la domain" characterization of quasi-Polish spaces.

Approximation spaces are exactly the spaces in which player NonEmpty has a winning memoryless strategy in the Choquet topological game where

- at its i-th-move player Empty plays a nonempty open set U_{2i} and a point x_i in U_{2i}. For $i \geq 1$, the set U_{2i} must be included in U_{2i-1}.
- at its i-th-move player NonEmpty plays a nonempty open set U_{2i+1} which must be included in U_{2i} and contain the point x_i.
- NonEmpty wins if and only if the intersection of the U_j's is nonempty.

A strategy for NonEmpty is convergent if the U_j's is a basis of neighborhoods of some point in the intersection of the U_i's. A strategy for NonEmpty is memoryless if its i-th-th move depends only on the i-th move of Empty.

We prove that a T_0 second-countable space is quasi-Polish spaces if and only if player NonEmpty has a winning convergent strategy if and only if player NonEmpty has a winning memoryless convergent strategy.

3.12 Clarke's Generalized Gradient and Edalat's L-derivative

Peter Hertling (Universität der Bundeswehr – München, DE)

Clarke (1973, 1975, 1983) introduced a generalized gradient for Lipschitz continuous functions on Banach spaces and a notion of upper semicontinuity for set-valued functions. He showed that the function that maps a point to its generalized gradient is upper semicontinuous in this sense if the underlying Banach space is finite-dimensional. Edalat (2005) posed the question whether this is true as well if the Banach space is infinite-dimensional. We show that the answer to this question is in general negative for upper semicontinuity in

Clarke's sense and positive for another notion of upper semicontinuity considered by Edalat. Furthermore, Edalat introduced as so-called L-derivative for real-valued functions, showed that it is identical with Clarke's generalized gradient if the underlying Banach space is finite-dimensional, and asked whether this is true also if the Banach space is infinite-dimensional. We show that this is the case.

3.13 Continuous domain theory in logical form

Achim Jung (University of Birmingham, UK)

In 1987 Samson Abramsky presented "Domain Theory in Logical Form" in the Logic in Computer Science conference. His contribution to the conference proceedings was honoured with the Test-of-Time award 20 years later. In this talk I will begin by giving a brief overview of this seminal work and then focus on three technical issues that (among others) Samson had to overcome in order to make DTLF work. These issues are chosen because they have proved to be particularly difficult to generalise to the continuous case. I will explain what is known about the generalisations and what the key open questions are.

3.14 On the duality between state transformer and predicate transformer semantics

Klaus Keimel (TU Darmstadt, DE)

Domain Theory provides two kinds of semantics for programs. State transformer semantics describes the input–output behavior of programs. Predicate transformer semantics at the contrary assigns to every (desired) property of the output the weakest precondition on the input which guarantees the (desired) property for the output. In several situations the two semantics have been proved to be dually equivalent.

For deterministic programs this is a straightforward but extremely useful observation for the verification of programs. It has been extended to non-deterministic programs by M. B. Smyth. For programs involving probabilistic features this has has been noted by D. Kozen and in a domain theoretical setting by C. Jones. For situations combining probabilistic and ordinary non-determinism, K. Keimel and G. D. Plotkin as well as J. Goubault-Larrecq have also established this dual equivalence. The methods needed for the proofs became more and more involved.

The question arises whether such a dual equivalence between predicate and state transformer semantics may be expected quite generally. The talk will be devoted to this question. We will show that such a dual equivalence can arise in quite special situations only.

We will use the continuation monad over a domain of 'observations' and monads subordinate to the continuation monad. Notions from universal algebra like entropicity will play a role. We will see that the commutativity of the monads is a property which is essential for the desired dual equivalence.

3.15 Perspectives on non-commutative Stone dualities

Ganna Kudryavtseva (University of Ljubljana, SI)

I will outline several approaches to non-commutative generalizations of Stone duality that have been developed in recent years. The general idea can be very briefly explained as follows: we consider an algebra that generalizes a Boolean algebra (or a distributive lattice, or a frame or a coherent frame...) and enquire how the dual topological (localic) object of the commutative structure can be upgraded to dualize the whole algebra. For more details, please see the extended abstract of my talk.

3.16 Endpoints of quasi-metric spaces

Hans-Peter Albert Künzi (University of Cape Town, ZA)

Joint work of Agyingi Collins Amburo; Haihambo Paulus; Kuenzi, Hans-Peter Albert
Main reference C. A. Agyingi, P. Haihambo, H.-P. A. Künzi, "Endpoints in T_0-Quasimetric Spaces: Part II," Abstract and Applied Analysis, Volume 2013, Article ID 539573, 10 pp. , 2013.
URL http://dx.doi.org/10.1155/2013/539573

In his well-known paper dealing with the construction of the injective hull of a metric space Isbell introduced the concept of an endpoint of a compact metric space.

In my talk I shall introduce similarly the notion of an endpoint in a joincompact T_0-quasi-metric space. It turns out that in a joincompact T_0-quasi-metric space there is a dual concept which I shall call a startpoint. Some classical results on endpoints in metric spaces can then be generalized to the quasi-metric setting.

In particular I shall specialize some of the results to the case of two-valued T_0-quasi-metrics, that is, essentially, to partial orders.

3.17 Computational Semantics for Intuitionistic Logic Using the Muchnik Lattice

Rutger Kuyper (Radboud University Nijmegen, NL)

Around 1960, Medvedev and Muchnik introduced two computationally motivated lattices in an attempt to capture the computational content of intuitionistic logic (as suggested by the BHK interpretation). Unfortunately, these two lattices (which are, in fact, Brouwer algebras, i.e. order duals of Heyting algebras) fall short: the satisfy the weak law of the excluded middle $\neg A \vee \neg\neg A$. Surprisingly, in 1988 Skvortsova showed that one can repair this deficiency by looking at a factor of the Medvedev lattice by a principal filter: there is a principal factor of the Medvedev lattice which exactly captures IPC. The analogous result for the Muchnik lattice was recently proven by Sorbi and Terwijn. Unfortunately, the elements generating these principal filters are unnatural, in the sense that they do not have clear computational interpretations. Therefore this does not completely give us computational semantics for IPC.

It turns out that, at least in the case of the Muchnik lattice, there are also natural factors which characterise IPC. I will explain how some well-known concepts from computability theory give us such factors.

3.18 Quasi-uniformities and Duality

Jimmie D. Lawson (Louisiana State University, US)

The duality of stably compact spaces and accompanying dualities of structures they carry have received considerable attention in recent work in the theoretical computer science community and beyond. We consider the duality of stably compact spaces as a special case of a natural duality of quasi-uniform spaces. We give an overview of some important aspects of the latter theory, make explicit connections with stably compact spaces through compactifications, and seek to identify cases where these compactifications can be characterized order theoretically as a special type of completion we call the D-bicompletion.

3.19 Category Theory vs. Universal Algebra in Duality Theory

Yoshihiro Maruyama, (University of Oxford, UK)

Duality theory has been developed mainly in two contexts: category theory and universal algebra. Based upon my recent work in both contexts, I aim at comparing the two ways of duality theory, thereby explicating what are genuine merits of each, and seeking new possibilities to integrate them. Especially, I shed light upon the distinction between finitary Stone dualities (e.g., in logic) and infinitary Stone dualities (e.g., in domain theory), with particular emphasis on links with dualities in algebraic geometry, and their dimension-theoretical consequences.

3.20 A microcosm principle in logic

Paul-Andre Mellies (University Paris-Diderot, FR)

The microcosm principle is a fundamental principle of higher-dimensional algebra, which states that every algebraic structure of dimension n needs an appropriate algebraic framework of dimension $n + 1$ in order to be formulated. Typically, the definition of a monoid in Set requires the category Set itself to be cartesian.

My main purpose in this introductory talk will be to describe a similar microcosm principle in logic. The principle expresses that every universe C of discourse (typically a Heyting algebra or a cartesian closed category) relies on the ability to define an opposite universe C^{op} by reversing the orientation of every logical implication in C. In the same way

as a change of frame of reference in galilean mechanics, this involutive operation $C \mapsto^{\mathrm{op}}$ performs a change of point of view between the two sides of the logical dispute. An important point is that every formula A seen in the universe C becomes its negation A^* when seen in the universe C^{op}.

In this way, every logical system (even intuitionistic) becomes equipped with an involutive negation $A \mapsto A^*$. By way of illustration, I will show how to decompose the implication $A \Rightarrow B$ of intuitionistic logic as a disjunction $A^* \vee B$, in exactly the same way as in classical logic. If time permits, I will briefly explain how this analysis is related to tensorial logic and to its purely logical reconstruction of game semantics.

Tentative references for the talk:

References

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3.21 Wadge-like reducibilities on arbitrary quasi-Polish spaces: a survey.

Luca Motto Ros (Universität Freiburg, DE)

Joint work of Motto Ros, Luca; Schlicht, Philipp; Selivanov, Victor

Main reference L. Motto Ros, P. Schlicht, V. Selivanov, "Wadge-like reducibilities on arbitrary quasi-Polish spaces," arXiv:1204.5338v2 [math.LO], 2013; accepted for publication in Mathematical Structures in Computer Science.

URL http://arxiv.org/abs/1204.5338v2

Wadge reducibility has been introduced as a tool for classifying subsets of zero-dimensional Polish spaces according to their (topological) complexity, and it has found many applications in both set theory (a branch of mathematical logic) and computer science (it is e.g. crucial for the classification of omega-regular languages recognized by various type of automata). In the last years, many mathematicians have worked on extending the analysis of the classical Wadge hierarchy to other kinds of reducibilities between subsets of various topological spaces, including arbitrary Polish spaces and spaces relevant to computer science, like ω-continuous domains. This naturally led to the project (initiated in the Dagstuhl seminar "Computing with infinite data: topological and logical foundations", 2011) of systematically classifying the degree-hierarchies that one obtains by considering Wadge-like reducibilities on arbitrary quasi-Polish spaces, a wide class which contains all the above mentioned spaces. So far we were able to obtain a quite nice picture, covering many interesting cases in a quite uniform way. In this talk I will survey the know results and put in evidence the main open problems in this area of research.

3.22 Epistemic updates on algebras, dynamic logics on an intuitionistic base, and their sequent calculi

Alessandra Palmigiano (University of Amsterdam, NL)

In this talk, I will give an overview of very recent results on dynamic epistemic logic, stemming from the research line which investigates dynamic epistemic logic with the duality toolkit. Each of these results stands on its own and could be presented in isolation; however, I will try and convey the outline of an emerging nonclassical theory of dynamic updates.

3.23 Pervin spaces and duality

Jean-Eric Pin (University Paris-Diderot, FR)

Joint work of Gehrke, Mai; Grigorieff, Serge; Pin, Jean-Eric

This lecture is based on a joint work with M. Gehrke and S. Grigorieff.

A Pervin space is simply a set equipped with a lattice of subsets. This notion suffices to define a natural notion of completion which is equal to the Stone dual of the lattice. Pervin spaces are actually a very special case of quasi-uniform space (to be precise, a quasi-uniform space is a Pervin sapce iff it is transitive and totally bounded). However, the theory becomes much simpler than for quasi-uniform spaces. For instance, a function f from (X, L_X) to (Y, L_Y) (L_X and L_Y are lattices of subsets) is uniformly continuous iff for each L in L_Y, $f^{-1}(L)$ belongs to L_X.

3.24 Relational semantics for the Lambek-Grishin calculus and extensions

Lorijn van Rooijen (University of Bordeaux, FR)

Joint work of Chernilovskaya, Anna; Gehrke, Mai; van Rooijen, Lorijn
Main reference A. Chernilovskaya, M. Gehrke, L. van Rooijen, "Generalised Kripke semantics for the Lambek-Grishin calculus," Logic Journal of the IGPL, 20(6):1110–1132, 2012.
URL http://dx.doi.org/10.1093/jigpal/jzr051

We present relational semantics for a substructural logic called the Lambek-Grishin calculus and various extensions. Following the approach of generalised Kripke semantics described in [2], we consider semantics based on the generalised Kripke frames naturally associated with the algebraic semantics of the logics in question via their representation theory. This approach is based on canonicity and correspondence as in the classical modal logic setting.

The approach via canonical extensions of LG-algebras provides the possibility of a modular treatment of various extensions of the Lambek-Grishin calculus. Additional axioms that lift to the canonical extension give additional first-order properties on the frame, whereas additional connectives modularly slot in as additional relational components.

All groups of additional axioms presented by Grishin in [3] are canonical, and we obtain correspondence results for each of these. The modular set-up allows us to augment these results by the correspondence results for associativity, commutativity, weakening and contraction from [1], and by results for additional connectives such as lattice operations and linear logic-type negation. This allows a clear comparison of the various logics and a fully modular family of completeness results.

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2 M. Gehrke. *Generalized Kripke Frames*. Studia Logica, volume 84:2, 241–275, 2006
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3.25 Intrinsic Sobriety

Giuseppe Rosolini (University of Genova, IT)

Joint work of Rosolini, Giuseppe; Bucalo, Anna
Main reference A. Bucalo, G. Rosolini, "Sobriety for equilogical spaces," to appear in Theoret. Comput. Sci.

The category of equilogical spaces, originally introduced by Dana Scott in his fundamental paper on Data Types as Lattices, is a locally cartesian closed extension of the category of topological spaces. Hence in that category, it is straightforward to consider (equilogical) spaces of continuous functions without bothering about suitable topologies. We test the power of this extension with the notion of sober topological space, producing an intrinsic characterization of those topological spaces which are sober in terms of a construction on equilogical spaces of functions.

3.26 Visser topology and other topologies from lambda calculus

Antonino Salibra (University of Venezia, IT)

Of great relevance for the lambda calculus is a topology, introduced by Visser in 1980, for sets which have an "effective" flavor. In the first part of the talk we describe applications of the Visser topology to the syntax and semantics of lambda calculus, and we present connections between the Visser topology and the Priestley topology. In the second part of the talk we introduce new separation axioms for topological algebras which are n-subtractive. n-subtractivity was introduced by the speaker to study the order-incompleteness problem of the lambda calculus.

3.27 Kleene-Kreisel Representations

Matthias Schröder (Universität Wien, AT)

A recent approach to Complexity Theory in Computable Analysis proposes to use representations that have Kleene-Kreisel spaces as their underlying spaces of names. By Kleene-Kreisel spaces we mean those spaces that can be constructed from the discrete natural numbers N by forming finite products, subspaces and function spaces.

We define and investigate Kleene-Kreisel representations. By constructing a Wadge-complete open set in the Kleene-Kreisel space N^{N^N} we prove that QCB-spaces embed into the category of Kleene-Kreisel representations via a functor that preserves binary products and function spaces.

3.28 A Universal Krull-Lindenbaum Theorem

Peter M. Schuster (University of Leeds, UK)

We formulate a natural common generalisation of Krull's theorem on prime ideals and of Lindenbaum's lemma on complete consistent theories. Our theorem not only has instantiations in diverse branches of algebra but also covers Henkin's approach to Gödel's completeness theorem. Following Scott we put the theorem in universal rather than existential form, which allows us to prove it with Raoult's Open Induction in place of Zorn's Lemma. By reduction to the corresponding theorem on irreducible ideals due to Noether, McCoy, Fuchs, and Schmidt, we further shed light on why transfinite methods occur at all.

3.29 Fine Hierarchies via Priestley Duality

Victor Selivanov (A. P. Ershov Institute – Novosibirsk, RU)

Main reference V. Selivanov, "Fine hierarchies via Piestley duality," Annals of Pure and Applied Logic, 163(8):1075–1107, 2012.
URL http://dx.doi.org/10.1016/j.apal.2011.12.029

In applications of the fine hierarchies [1], their characterizations in terms of the so called alternating trees are of principal importance. Also, in many cases a suitable version of many-one reducibility (m-reducibility for short) exists that fits a given fine hierarchy. With a use of Priestley duality we obtain a surprising result that suitable versions of alternating trees and of m-reducibilities may be found for any given fine hierarchy, i.e. the methods of alternating trees and m-reducibilities are quite general, which is of some methodological interest.

Along with the hierarchies of sets, we consider also more general hierarchies of k-partitions and in this context propose some new notions and establish new results, in particular extend the above-mentioned results for hierarchies of sets. Some preliminary results on the hierarchies of k-partitions may be found in [2, 3, 4].

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3 S. Kosub. NP-Partitions over posets with an application to reducing the set of solutions of NP problems. *Theory of Computing Systems*, 38(1): 83–113 (2005).
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3.30 Overt Subspaces of $\mathbb{R}^n$

Paul Taylor (UK)

URL http://www.paultaylor.eu/drafts/overtrn.pdf
URL http://www.paultaylor.eu/drafts/overt.bib
URL http://www.paultaylor.eu/drafts/overt-brainstorm
URL http://www.paultaylor.eu/slides/13-PSSL-Sheffield.pdf

Overt spaces and subspaces have arisen under different names in several constructive settings: open locales, positive formal spaces and locates subspaces in analysis. However, each discipline has presented it in its own formal notation with little attempt to draw the bigger picture for the benefit of colleagues, students or classical mathematicians.

One difficulty with this notion is that it dissolves into nothing in the classical setting. However, the way in which classical mathematicians handle the issues that we would consider constructively is to make things continuous in a parameter, so my starting point is to say that an overt subspace is a fibre of an open map.

A function $f : X \to Y$ between locally compact metric spaces is continuous and open iff

$$d_{y(x)} \equiv \inf\{d(x,a) \mid f(a) = y\}$$

defines a jointly continuous function $d : X \times Y \to \mathbb{R}$, thereby linking open maps to located subspaces. An overt subspace may be characterised in the same way but without the parameter y.

The basic technical result is that predicates on the lattice of open subspaces of a locally compact metric space X take take unions to disjunctions correspond to upper semicontinuous functions $d : X \to \mathbb{R}$ with the properties that

$$d(x) < r \iff \exists r'.d(x) < r' < r$$
$$d(x) < r \implies \forall \epsilon > 0.\exists x'.d(x') < \epsilon \wedge d(x,x') < r$$
$$d(x) < r \wedge d(x,y) < s \implies d(y) < r + s$$

The second property invites iteration, converging to a limit a, so that

$$d(x) < r \text{ iff } \exists a.d(x,a) < r \wedge d(a) = 0$$

where $d(a) = 0$ means $\forall r > 0.d(a) < r$, and we call such a an *accumulation point*.

If we think of $\diamond U$ as saying that the open subspace "ought" to contain a solution of a problem encoded by the operator $\diamond$ then this result says that it does contain such a solution (accumulation point).

I call this the *tangency theorem*. It is a topological (special) case of the *existence property*.

My characterisation above does not assume that the distance d takes (Euclidean) real values or that the subspace of accumulation points is closed. However, these two additional conditions are equivalent.

The first two of the three properties of d above are satisfied by the estimate that the Newton–Raphson algorithm provides for (the next iteration of) the solution of an equation involving a differentiable function.

This account of overt subspaces is valid

- but trivial in classical point–set topology,
- in intuitionistic local theory,
- in Formal Topology and
- in Abstract Stone Duality.

However, these theorems have different logical strengths, because each of these theories defines a different class of functions.

3.31 Computability, lattices, and logic

Sebastiaan A. Terwijn (Radboud University Nijmegen, NL)

The Medvedev lattice is a structure from computability theory that was introduced in order to obtain a connection with intuitionistic logic, but that also turned out to be interesting in its own right. Nowadays the notion of Medvedev reducibility is used to classify sets of reals from various areas, such as computable analysis, algorithmic randomness, reverse mathematics, and Π^0_1 classes. In this talk we discuss the logics connected to factors of the Medvedev lattice and the closely related Muchnik lattice. Skvortsova proved that there is a factor of the Medvedev lattice that captures intuitionistic propositional logic IPC. In joint work with Sorbi we recently obtained an analog of this theorem for the Muchnik lattice. This makes use of an earlier characterization of the finite intervals of the Muchnik lattice. Finally, we discuss natural factors and a conjecture about the set of complete extensions of PA.

3.32 The separation problem for regular languages

Marc Zeitoun (University of Bordeaux, FR)

Joint work of Place, Thomas; van Rooijen, Lorijn; Zeitoun, Marc
Main reference T. Place, L. van Rooijen, M. Zeitoun, "Separating Regular Languages by Piecewise Testable and Unambiguous Languages," in Proc. of the 38th Int'l Symp. on Mathematical Foundations of Computer Science (MFCS'13), LNCS, Vol. 8087, pp. 729–740, Springer, 2013.
URL http://dx.doi.org/10.1007/978-3-642-40313-2_64

Separation is a classical problem asking whether, given two sets belonging to some class, it is possible to separate them by a set from another class. We discuss the separation problem, and we present separation algorithms of regular languages for several classes of separators.

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Report from Dagstuhl Seminar 13312

"My Life, Shared" – Trust and Privacy in the Age of Ubiquitous Experience Sharing

Edited by

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Abstract

Many researchers have already begun using personal mobile devices as personal "sensing instruments" and designed tools that reposition individuals as producers, consumers, and remixers of a vast openly shared public data set. By empowering people to easily measure, report, and compare their own personal environment, such tools transform everyday citizens into "reporting agents" who uncover and visualize unseen elements of their own everyday experiences. This represents an important new shift in mobile device usage – from a communication tool to a "ubiquitous experience sharing instrument". This report documents the program and the outcomes of Dagstuhl Seminar 13312 *"My Life, Shared" – Trust and Privacy in the Age of Ubiquitous Experience Sharing*, which brought together 33 researchers and practitioners from multiple disciplines – including economics, psychology, sociology, as well as various fields within the discipline of computer science dealing with cryptographic feasibility, scalability and usability/acceptability – to discuss opportunities and challenges of sharing information from the pervasive environment.

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1 Executive Summary

Alessandro Acquisti
Ioannis Krontiris
Marc Langheinrich
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Advancements in smart phones and sensing technology have bolstered the creation and exchange of user generated content, resulting in new information flows and data-sharing applications. Through such applications, personal mobile devices are used to uncover and share previously private elements of people's own everyday experiences. Examples include using smartphones or wearable sensors to collect and share context information (e.g., activities, social context, sports performance, dietary or health concerns). These flows of personal

information have two distinct characteristics: they happen seamlessly (in real time, without necessarily the conscious participation of the user), and they are shared with a user's family, social circles, or even publicly.

This new paradigm repositions individuals as producers, consumers, and remixers of a vast set of data with potential many economic and societal benefits. However, as sharing practices become more fluid than in desktop-based online environments, control over personal information flows becomes harder to maintain.

The goal of Dagstuhl Seminar 13312 *"My Life, Shared" – Trust and Privacy in the Age of Ubiquitous Experience Sharing* was to advance a research agenda in trust and privacy that addresses not only the evolution of the pervasive technologies underlying these trends (e.g., smartphones, wearable sensors), but also the surrounding societal and economic context, and to identify the resulting qualitative changes to the privacy landscape.

With that in mind, the seminar created an interdisciplinary discussion forum and a set of organised presentations around four broad areas: 1) tools and protocols, 2) usability and control tools, 3) behavioural decisions, and 4) social implications. Each area saw a selected set of participants present their work and views in the context of a short presentation, followed by an in-depth discussion session. From these discussions the organizers collected the main challenges and opportunities, and grouped them around four major themes: "Personal Data Services", "Social Justice", "Tool Clinics", and "Consequence-based Privacy Decision-making". Each theme was subsequently discussed during one and a half days in four individual working groups, which presented their findings at the end of the seminar.

This report not only contains the abstracts of the initial presentations (section 3) but also the findings of the four thematic working groups. Below we summarize the main findings from these working groups – a more analytical description can be found in section 4.

Theme 1: Personal Data Service (PDS)

A "Personal Data Service (PDS)" represents a trusted container for aggregating, storing, processing and exporting personal data. In principle, all data regarding the user (either user-generated or obtained from other sources, e.g. service providers) should be accessible to this container, including data about the user collected and published by others. Users are in control of all data stored in the PDS, which includes the option to share or sell parts of this data. In addition to storing data, the PDS can execute code to process this data locally.

By considering both a household- and a health-related scenario, the working group identified some of its properties and functionalities and sketched a possible system architecture that would include such a container. In a detailed discussion of benefits and risks, the working group concluded that there were still several issues to be investigated and real challenges that needed to be addressed before a PDS framework could be implemented and deployed, such as:

- Creating *incentives* to initial data providers to engage and open up the personal data APIs that are needed to fuel the PDS and associated applications.
- Creating *utility* from stored data: data fusion, sense making, and visualization that will lead to meaningful and actionable and sustainable engagement of the end user with their data.
- Addressing *privacy*: even though the PDS can increase transparency, awareness and engagement of users with their data, it is neither obvious nor guaranteed that PDS will resolve user privacy problems and several of them remain open.

Theme 2: Social Justice

Privacy issues in participatory sensing are symptoms of broader concerns about the impact of sensing on social justice. Framing a social justice research agenda for participatory sensing requires the operationalization of concepts like fairness, human flourishing, structural change, and balances of power for system design, use, and regulation. The working group discussed how one might begin to operationalize these concepts for the design of data collection features, processing, sharing, and user interfaces. The group developed an analysis tool – a social justice impact assessment – to help system designers consider the social justice implications of their work during the design phase. The participants identified and presented several open questions that could spark future research, such as:

- If one assumes that participatory sensing will lead to *greater transparency*, will such transparency equally impact individuals, powerful people, and institutions?
- Do the powerful always end up *subverting transparency* schemes? Or can sensing change that tendency, for example by making facts visible to consumers and citizens, enabling organized responses (unionization)?
- What are the forums for *encouraging collective action* in participatory sensing? Can one encourage system designers to consider social justice during design by framing design as a collective action problem? Can participatory sensing open new avenues for consumers and citizens to organize collective action?

Theme 3: Tool Clinics

Privacy researchers and practitioners are working largely in isolation, concentrating on people's use of different user interfaces for privacy control, largely ignoring existing cross-disciplinary collaboration techniques. A "tool clinic" could encourage a collaborative (re)consideration of a technological solution, research technique or other artefact, in order to critically assess its design, development and deployment from multiple perspectives. A tool clinic can be used to provide a setting for those who are developing the solutions to rethink the framing and presentation of their solutions. The objective is to reflect from different perspectives on practices around the development, encoding, use, domestication, decoding and sustainability of a tool to gain quasi-ecological validation. The working group recommended to develop a tool clinic as a new event format for a scientific conference, ideally at a renowned computer-science conference. This would combine the tool-centric nature of a demo session, the protected space of work-in-progress afforded by a workshop, and the mentoring spirit of a doctoral workshop. The format of a tool clinic session could typically consist of three steps:

1. Identifying particular affordances of the technological solution, research technique or other artefact and possible (unintended) consequences for people and society;
2. Gathering perspectives and practices of different experts, disciplines and/or stakeholders (e.g. users, policy makers, industry, etc.) linked with the development, deployment and sustainable evolution of a particular tool, solution, technique or artefact;
3. Informing and advising on technological design of the tool or solution, in order to avoid negative consequence and to further positive outcome.

Theme 4: Consequence-based Privacy Decisions

Recent research shows that people not only want to control their privacy but are actually trying to do so. An appropriate privacy-respectful user interface should thus show users the consequences of making different privacy choices, rather than framing the choices only in technical terms regarding system parameters, which users often do not understand and do

not care about. Providing tools to increase user comprehension of potential consequences is one of the next big challenges to be addressed in the field of privacy respectful user interfaces. In addition to helping users make better choices in terms of privacy protection, this will also allow them to make better informed decisions and hence, implement the notion of informed consent. The attempt to develop user interaction in this direction requires research on a number of issues that have so far received relatively little attention and concern, such as:

- *Expression of potential consequences:* The consequences should be expressed in a way that is comprehensible by different user categories from novices to experts.
- *Decision support:* Users could be further helped in their privacy decisions by external information sources. Studies to determine the responses to different kinds of information sources, different formats, and information from different groups of users will be necessary.
- *Minimal effort:* Introducing additional tools to help users make informed decisions may add significant overhead to the interaction. While this overhead may be the price to pay for better privacy protection, it should be limited to the minimum.

2 Table of Contents

3 Overview of Talks

The first three days of the seminar saw a range of short presentations from a subset of seminar participants, grouped into four areas: 1) tools and protocols, 2) usability and control tools, 3) behavioural decisions, and 4) social implications. The goal was to create a common understanding between the diverse set of participants and to stimulate discussions about opportunities and challenges in the space. Below, we provide the abstracts of the 15 talks that were given by individual seminar participants, in alphabetical order.

3.1 Gone in 15 Seconds: The Limits of Privacy Transparency and Control

Alessandro Acquisti (Carnegie Mellon University, US)

I will present some results from privacy experiments inspired by behavioral economics and decision research. The experiments investigate the role of control and transparency in privacy decision making. The results suggest that even simpler or more usable privacy notices and controls might not improve users' decision-making regarding sharing of personal information: Control might paradoxically increase riskier disclosure by soothing privacy concerns; transparency might be easily muted, and its effect even arbitrarily manipulated, through simple framing or misdirections.

3.2 Privacy and Location Sharing: Challenging Technical Problems in Search for Conscious Users

Claudio Bettini (University of Milan, IT)

Among the many types of data that are shared as part of social online interactions, we focus on spatio-temporal data and on the privacy issues involved in sharing users' location and movements. We illustrate some of the technical challenges in the design of location privacy protection and location sharing monitoring tools, considering in particular the threats involved in posting geo-tagged resources in OSN, and the ones determined by location sharing in proximity services. We also report on our recent experience with the design, implementation and offering on the global market of PCube, a friend-finder mobile app that totally hides location and proximity information to the service provider. We will discuss the feedback obtained by users, the actual challenges we faced, and, in general, the lessons learned.

3.3 Collective Exposure: Peer Effects in Voluntary Disclosure of Personal Data

Rainer Böhme (Universität Münster, DE)

Joint work of Böhme, Rainer; Pötzsch, Stefanie
Main reference R. Böhme, S. Pötzsch, "Collective Exposure: Peer Effects in Voluntary Disclosure of Personal Data," Financial Cryptography 2011:1–15.
URL http://dx.doi.org/10.1007/978-3-642-27576-0_1

I will report empirical evidence for peer effects in privacy behavior using field data from Germany's largest online social lending platform. The study applies content analysis to measure personal data disclosure on and identifiability of borrower profiles with tailored scales. A logistic regression analysis suggest that individuals tend to copy observable behavior of others in their decisions on

- how much to write about oneself,
- whether to share custom pictures,
- what personal data to disclose, and
- how identifiable to present oneself.

I will frame this finding in the theory of descriptive social norms and explore moderating effects, such as similarity of context, social proximity, and mimicry of success factors. Peer effects in disclosure behavior seem to be an important factor to explain the formation and change of apparent social norms and attitudes towards information privacy. [1]

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3.4 Transparency, Control, Minimisation, Law – How to Build Societal Trust in Ubiquitous Sharing?

Ian Brown (University of Oxford, GB)

Main reference I. Brown, "Lawful Interception Capability Requirements," Computers & Law 24(3), 2013.
URL http://www.scl.org/site.aspx?i=ed32980

Edward Snowden's dramatic revelations about the broad surveillance activities of the US National Security Agency have been called the most important leaks in American history. It seems the UK's equivalent intelligence agency, GCHQ, is equally busy wiretapping the world's Internet traffic.

What implications do these surveillance systems have for ubiquitous experience sharing systems? How can data privacy be protected in a world with such voracious intelligence agencies? And what responsibilities does this place on life logging system designers?

3.5 Tools of the Trade: Enhancing Privacy in Participatory Sensing

Tassos Dimitriou (Athens Information Technology, GR)

In this presentation we review some of the private-preserving mechanisms applied in participatory sensing applications. We start with a definition of privacy for participatory sensing and the threats associated with uncontrolled disclosure of sensitive information. We then consider typical countermeasures used by the various architectural elements of sensing applications. Finally, we highlight and discuss some interesting research directions that must be addressed to enhance user privacy and encourage user participation.

3.6 Sharing Private Location Information via Non-trusted Servers

Frank Dürr (Universität Stuttgart, DE)

Joint work of Dürr, Frank; Rothermel, Kurt; Skvortsov Pavel; Wernke, Marius

Private location information is essential for many modern location-based services like geo-social networks. Often, such services are hosted on third- party server infrastructures ("in the cloud"). We argue that it is practically impossible to guarantee that private location information stored on such infrastructures is perfectly protected from unauthorized access. Many incidents in the past have shown that private data managed on "trusted" and protected servers was stolen or "leaked". Consequently, we think there is no such thing as a trusted server, and we have to think about technical concepts to protect private information shared through non- trusted server infrastructures.

Besides highlighting the problem, we are going to present technical concepts for the management of private location information on non-trusted servers. Our concepts include some very interesting features such as no single point of failure, graceful degradation of privacy with the number of compromised servers, and the possibility to define different levels of privacy for different location-based applications to defined a trade-off of quality of service and privacy. Moreover, we briefly present a second concept for protecting information derived from movement trajectories, namely speed information, by limiting the accuracy of spatial-temporal information.

3.7 Location Privacy – Myth or Reality?

Raghu K. Ganti (IBM TJ Watson Research Center – Yorktown Heights, US)

Joint work of Srivatsa, Mudhakar; Agrawal, Dakshi; Abdelzaher, Tarek; Lee, Kisung; Liu, Ling; Pham, Nam; Han, Jiawei; Wang Jingjing

As spatiotemporal data generated by mobile devices become readily available and increase in volume, a critical and important question that arises is that of location privacy. On one hand, location and time data enable novel applications and services to the common man (e.g.,

smarter cities, smarter telcos). On the other hand, such information can result in serious privacy breaches (e.g., pleaserobme.com). In this talk, I will examine the implications of availability of large volumes of spatiotemporal data on privacy. I will present observations from our past work on the privacy analysis of spatiotemporal data, examining various techniques to obfuscate such data to achieve privacy at a community-wide level and also examining techniques that break the privacy based on different channels of information (e.g., text, maps). Finally, I will also discuss a system that we are currently building that can ingest large volumes of data and analyze it in real-time to infer motion behavioral patterns.

3.8 Toying with Facebook: An Online Experiment of Privacy Authorization Dialogues for Social Applications

Jens Grossklags (Pennsylvania State University, US)

Main reference N. Wang, J. Grossklags, H. Xu, "An online experiment of privacy authorization dialogues for social applications," in Proc. of the 2013 Conf. on Computer Supported Cooperative Work (CSCW'13), pp. 261–272, ACM, 2013.
URL http://dx.doi.org/10.1145/2441776.2441807

Several studies have documented the constantly evolving privacy practices of social networking sites and users' misunderstandings about them. Researchers have criticized the interfaces to "configure" privacy preferences as opaque, uninformative, and ineffective. The same problems have also plagued the constant growth of third-party applications and their troubling privacy authorization dialogues. In this talk, I report the results of an experimental study examining the limitations of current privacy authorization dialogues on Facebook as well as four new designs which were developed based on the Fair Information Practice Principles (FIPPs). Through an online experiment with 250 users, the effectiveness of installation-time configuration and awareness-enhancing interface changes are studied. The experimental results are complemented with data from a measurement study on Facebook third-party applications.

3.9 Two Tales of Privacy in Online Social Networks

Seda F. Gürses (KU Leuven, BE)

Joint work of Gürses, Seda F.; Diaz, Claudia
Main reference S. Gürses, C. Diaz, "Two tales of privacy in online social networks," IEEE Security and Privacy, 11(3):29–37, 2013.
URL http://dx.doi.org/10.1109/MSP.2013.47
URL http://www.cosic.esat.kuleuven.be/publications/article-2270.pdf

Privacy is one of the friction points that emerges when communications get mediated in Online Social Networks (OSNs). Different communities of computer science researchers have framed the 'OSN privacy problem' as one of surveillance, institutional or social privacy. In tackling these problems they have also treated them as if they were independent. We argue that the different privacy problems are entangled and that research on privacy in OSNs would benefit from a more holistic approach. During my talk, I will first provide an introduction to the surveillance and social privacy perspectives in computer science emphasizing the narratives

that inform them, as well as their assumptions, goals and methods. I will then juxtapose the differences between these two approaches in order to understand their complementarity, and to identify potential integration challenges as well as research questions that so far have been left unanswered.

3.10 Planning your Digital Afterlife – User Needs and Control Tools

Thomas Heimann (Google – München, DE)

Joint work of Micklitz, Stephan; Ortlieb, Martin; Staddon, Jessica
Main reference S. Micklitz, M. Ortlieb, J. Staddon, "'I hereby leave my email to...': Data Usage Control and the Digital Estate," in Proc. of the 2013 IEEE Security and Privacy Workshops (SPW'13), pp. 42–44, 2013.
URL http://dx.doi.org/10.1109/SPW.2013.28

While we have established procedures for inheriting tangible items, our practices for inheriting digital assets are far less developed. Giving users control over their "digital estate" is becoming more and more important as the volume and importance of digital artifacts grows. Like physical possessions, digital artifacts may carry significant sentimental value for bereaved family members, and tools for managing the digital estate may help to remember, commemorate, and reminisce about the deceased and find closure.

Google's Inactive Account Manager provides Google users with the opportunity to manage if and how their data is made available to specified trustees in the case of death or temporary unavailability. In this presentation, I present some of the research, design and implementation challenges that accompanied the development of this feature.

3.11 Move Over, Westin

Anthony Morton (University College London, GB)

Joint work of Morton, Anthony; Sasse, Martina Angela
Main reference A. Morton, M. A. Sasse, "Privacy is a process, not a PET: a theory for effective privacy practice," in Proc. of the 2012 Workshop on New Security Paradigms (NSPW'12), pp. 87–104, ACM, 2012.
URL http://dx.doi.org/10.1145/2413296.2413305

Researchers and practitioners have continued to use Westin's categorisation of people into privacy fundamentalists, privacy pragmatists and privacy unconcerned, even though it has not yet been shown to be a reliable predictor of people's privacy behaviour. A simple, three-level categorisation is flawed for two reasons: 1) people's privacy concern is dynamic – not static – and is influenced – amongst other things – by the perceived sensitivity of the information collected or requested, the purpose of collection, and the party requesting it; and 2) with the increasing power and ubiquity of technology to collect, process, store and disseminate information, a more comprehensive representation of people's'privacy concern is required. To address these weaknesses, we propose a richer model of privacy concern, encompassing: a) dispositional privacy concern; b) privacy concern due to environmental factors (e.g. the experiences of friends and family); and c) privacy concern specific to the technology- mediated interaction with the other party. In addition, as privacy concern is widely recognised as being subjective, we also describe an innovative use of Q methodology –

a research method which combines qualitative and quantitative research methods to identify people's subjective viewpoints – to determine if it is feasible to group people into segments representing different privacy attitudes, and hence specific configurations of our proposed richer model of privacy concern. Finally, we consider what is a 'reasonable' level of privacy concern? When does a person's desire for privacy, or concern about information collection, become paranoia?

References

1 Adams, Anne, and Martina Angela Sasse. *"Privacy in multimedia communications: Protecting users, not just data." People and Computers XV – Interaction without Frontiers.* Springer London, 2001. 49- 64.

3.12 Theatre, Mirror, or Laboratory: Cross-Purposes in Platforms of Intimate Knowledge

David Phillips (University of Toronto, CA)

Joint work of Phillips, David; Harding, Brian; Leighton, Danielle

In this presentation I briefly suggest several reasons why individuals create, collect, share, and analyze intimate data about themselves. I then discuss the tools with which they pursue these interests, and the infrastructures by which they access these tools. I review the economic and social models which support those infrastructures, and finally, probe some of the tensions among these various interests.

3.13 The Right Privacy Controls for Social Search

Sören Preibusch (Microsoft Research – Cambridge, GB)

URL http://preibusch.de/

We share our lives, as the motto of our seminar evokes, but Web search, the most ubiquitous of Web activities, is still very much a solitary pursuit. This is particularly surprising, as our lives can be told in queries: interests and preferences, goals and unsatisfied needs. As we prepare for social search, how should we engineer a shared search experience? Social search promises to improve the relevance of results by taking into account the social connections of the searcher. One aspect of social search is the collaborative search experience, where one can inspect and learn from friends' queries, results, and clicked links. Results are discovered and ranked by borrowing from similar queries that our friends have issued in the past, and the Websites they subsequently visited. However, a sizeable proportion of everyday queries are better kept private, such as health issues, surprise gifts or porn. Acceptance of social search will hinge on users keeping control over which queries to share and which queries to keep private. I will report on a recent large-scale laboratory experiment into ways user manage their privacy when using a Web search engine: privacy features are universally appreciated and usage is high. A sizable proportion of users is willing to pay for added privacy. Although usage decisions were found not to be systematically dependent on

consumers' privacy preferences, the sensitivity of the topic has a significant impact on the demand for privacy.

3.14 User-Controllable Privacy: An Oxymoron?

Norman Sadeh (Carnegie Mellon University, US)

Increasingly users are expected to evaluate and configure a variety of privacy policies (e.g. browser settings, mobile app permissions, or social networking accounts). In practice, research shows that users often have great difficulty evaluating and configuring such policies. As part of this presentation, I will provide an overview of research aimed at empowering users to better control their privacy in the context of a family of location sharing applications we have deployed over the years. This includes technologies to analyze people's privacy preferences and help design interfaces that are capable of effectively capturing their desired policies. This research helps explain why, with the possible exception of Foursquare, applications in this space have failed to gain traction and what it will likely take to go beyond the mundane scenarios captured by Foursquare. Part of this talk will be devoted to user-oriented machine learning techniques intended to reduce user-burden and help users converge towards policies they feel more comfortable with. Beyond location sharing, this talk will also discuss our longer-term goal of developing personalized privacy assistants (or "agents") capable of engaging in dialogues with users to help them semi-automatically evaluate privacy policies and configure privacy settings.

3.15 Experience Sharing & Social Justice

Katie Shilton (University of Maryland – College Park, US)

I will argue that privacy issues in participatory sensing are symptoms of broader concerns about the impact of sensing on social justice. Framing a social justice research agenda for participatory sensing challenges us to operationalize concepts like fairness, human flourishing, structural change, and balances of power for system design, use, and regulation. I will discuss how we might begin to operationalize these concepts for the design of data collection features, processing, sharing, and user interfaces. And I will explores how we can encourage participatory sensing designers to consider these challenges as collective action problems.

4 Working Groups

After three days of presentations and discussions, the participants identified four major themes that are of relevance in pervasive experience sharing: "Personal Data Services", "Social Justice", "Tool Clinics", and "Consequence-based Privacy Decision-making". Each theme was subsequently discussed during one and a half days in four individual working

groups, which presented their findings at the end of the seminar. The four sections below constitute the output of each of these working groups.

4.1 Personal Data Service: Accessing and Aggregating Personal Data

Alessandro Acquisti (Carnegie Mellon University, US)
Claudio Bettini (University of Milan, IT)
Rainer Böhme (Universität Münster, DE)
Claude Castelluccia (INRIA Rhône-Alpes, FR)
Tassos Dimitriou (Athens Information Technology, GR)
Frank Dürr (Universität Stuttgart, DE)
Deborah Estrin (Cornell Tech NYC, US)
Michael Friedewald (Fraunhofer ISI – Karlsruhe, DE)
Raghu K. Ganti (IBM TJ Watson Research Center – Yorktown Heights, US)
Jens Grossklags (Pennsylvania State University, US)
Renè Mayrhofer (University of Applied Sciences Upper Austria, AT)
David Phillips (University of Toronto, CA)
Kai Rannenberg (Goethe-Universität Frankfurt am Main, DE)
Norman Sadeh (Carnegie Mellon University, US)
Marcello Scipioni (University of Lugano, CH)

4.1.1 Motivation

The last decade has seen a major trend towards personal data analysis: in addition to purely digital services such as social networks, we have observed an increasing integration of real-world sensing from various sources, including digital traces from online search, shopping, social, entertainment and financial services; fitness applications; medical sensing; as well as environmental, vehicular, and household data. So far, these data sources are mostly handled as separate streams: they are collected, stored, and analyzed within their own commercial niches – typically out of view of the individual whose life they describe. One foreseeable trend is the aggregation of different data streams about the individual, in order to facilitate better data utilization by correlating and generally combining across data streams, and bringing the individual in control over the aggregated use of these data.

Current digital service providers like Google or Facebook may be more than likely to provide such an aggregation, analysis, and reporting service for their users free of charge – in return for getting an even more detailed picture of the individual, but thereby raising privacy concerns. Personal Data Services (PDS) are an alternative aggregating platform under control of the end user.

We use two common scenarios (a household shared by a family, and health data about a single individual) to define PDS, discuss their potential benefits and risks, and propose potential architectures for implementation.

4.1.2 Household Scenario

Consider the following data streams that are relevant to a typical household (be that an individual or a family unit):

- Transaction streams concerning payments, potentially spanning multiple vendors, different people, and different payment cards. As a key example, consider the possibility of a family wanting to reduce the amount of processed foods containing high salt and sugar content, or to increase the regularity of family meals. To track progress or to create social games that incentivize families or individuals within families, these transaction traces could be used as the measurement feedback. For independent living seniors, these transaction traces can also contribute to a wellbeing pulse shared with close family or friends, to help them stay aware of important but subtle changes that might benefit from intervention.
- Data on transportation, including public transportation, car usage, gas purchases, parking and toll fees, etc. A family wishing to reduce costs or increase sustainability could similarly use apps that analyze digital traces to make recommendations and incentive the desired behaviour. Communities and employers could sponsor "drives" or challenges in which progress as a community gets matched by corporate dollars to develop community resources, such as community gardens or green spaces.
- Household usage data, including utilities such as electricity, water, gas, etc. as typically measured by smart meters. These data can be aggregated into transportation based applications described above to create a bigger picture sustainability app. They can also be combined with transaction data to contribute to the overall wellbeing pulse because they capture what might be significant changes in behaviour such as decline home preparation of food, or change in diurnal patterns (when the coffee pot is used or increased night time activity).
- Time-activity-location data, including data from cellular network providers, location based services (foursquare), activity monitoring devices (Fitbit, Nike plus, Jawbone Up), and mobile apps. These data provide a baseline of individual and family patterns that can fuel family management, wellness, health, financial and other applications in combination with the other data streams described.

4.1.3 Health scenario

In this scenario we consider the streams of data that may be useful to collect and analyse to enable useful services related to an individual's health and well-being. We identify the following relevant sources of data:

- Mobile phone. A lot of potentially useful data comes from the digital traces we leave in our interaction with smartphones including temporal patterns of interactions with the apps, the user location and movements, user activities and more.
- Home appliances and sensors. Home automation is making available data that provide information about activities of individuals within their home (e.g., TV usage patterns, use of appliances for cooking, lights, heating, room occupation, etc.)
- Medical and fitness-specialized sensors. Wearable sensors like Nike FuelBand, Jawbone Up, Fitbit Flex, or Misfit Shine are becoming common and can reveal levels of physical activity, type of activity, sleep patterns and more. Other useful data can be morning and evening blood pressure or morning weight. All of this data can be integrated into the PDS, perhaps through commercial third parties (e.g., Qualcomm Life 2net).

- External data sources from service providers (e.g., data about purchased food products obtained from merchants, data about media consumption from a cable company, data about physical training from the gym, data from EHR, etc.)
- Public and environmental data sources (e.g. pollution maps, weather reports, etc.)

4.1.4 Personal Data Service

We define a Personal Data Service (PDS) as a user trusted container for aggregating, storing, processing and exporting Personal Data. In principle, all data regarding the user (either user-generated or obtained from other sources, e.g. service providers) should be accessible to this container, including data about the user collected and published by others. Users are in control of all data stored in the PDS, which includes the option to share or sell parts of this data. In addition to storing data, the PDS can execute code to process this data locally, and will in turn store the processed data alongside the raw source data.

4.1.5 PDS functionality and architecture

By considering the two scenarios illustrated above we expect a PDS to perform the following functions:

- To access, protect, and analyze the incoming data streams for different sources for overall fusion of the data and local storage of resulting derived data.
- To provide an open third-party marketplace of apps with local processing, filtering, and auditing of user privacy preferences and actions of the applications.
- To support exporting locally derived data (e.g. about car usage in the household scenario) to third-party application providers with filtering and transformation for privacy reasons, and strong auditing.

In Figure 1 we illustrate a possible architecture for the interaction between a PDS and other software components and entities. The architecture in Figure 1 refers in particular to the household scenario.

In the health related scenario, we can foresee a similar architecture, with the PDS playing a major role for the following:

- For medical use of the data by patients as well as by clinicians through dedicated software, exporting data either filtered (for privacy control) or raw.
- For individual summaries/reports with aggregated data or to generate specific alerts.
- To export to existing healthcare systems (e.g., Ginger.io).

4.1.6 Privacy Impact of PDS

We explicitly note that the main goal of a PDS is utility as emphasized in the description of its functionalities with respect to our scenarios.

Many of state-of-the-art privacy preserving methods, based for example on obfuscation or generalization of sensitive personal information, can be applied in the PDS as part of the filtering functionality for exporting personal data. They can also be coupled with advanced access control methods. However, despite filtering, a PDS is NOT by itself a privacy preserving technology. Indeed, relevant personal data are also independently acquired and held by third parties.

The PDS is a tactical move to increase transparency, awareness, and engagement of users with their data. This by itself is a significant step along the lines of the recent EU proposal for a new data protection regulation that emphasizes the need to increase transparency, user

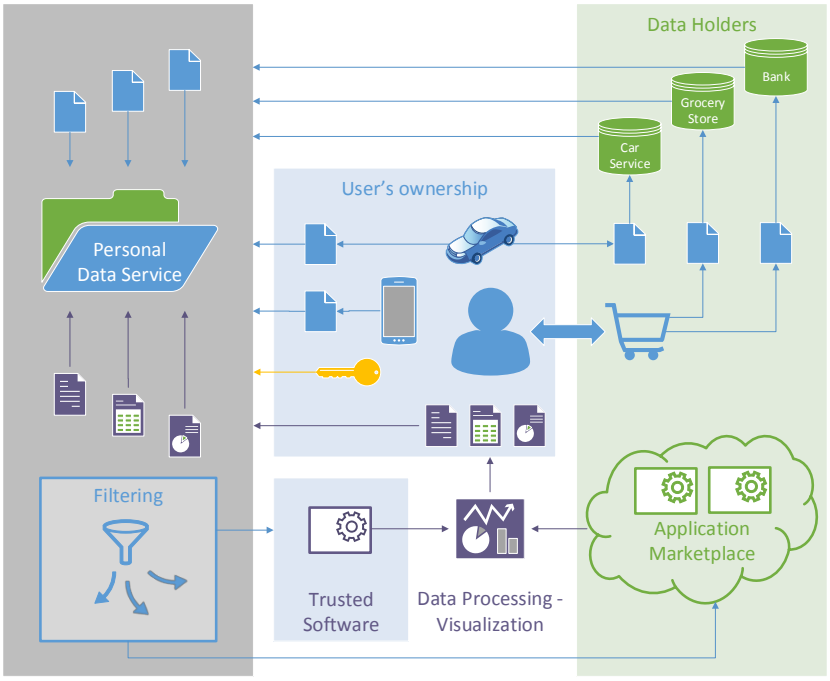

Figure 1 The PDS architecture in the household scenario.

awareness and control together with the principles of privacy by default and the right to be forgotten.

The PDS may also contribute to shift the market to a different behaviour through standardization of personal data formats and APIs to store and retrieve personal data. However, ultimate impact on privacy and alignment with diverse national policy frameworks will still depend on regulation of data service providers to support the particular country's sovereignty to enforce local policy.

4.1.7 Benefits of a PDS framework

We can identify the following benefits:

- Transparency to users of, and engagement of users with, data collected about them, e.g., increase privacy when it comes to processing across diverse data streams including counter-surveillance and the opportunity for the individual to validate the integrity of the data.
- A context in which to develop and support domain specific identity management so that individuals can configure appropriate roles and associated data sharing and not have one size fits all identity and data sharing with third party services.
- Catalyzing a new ecosystem of innovations in personal services from commuting to consumption, entertainment and health/wellness. This will have the dual benefit of utility to the individual and economic growth of this new sector.
- The potential to support consumer groups and movements by giving them more collective power through their access and use of the individual and community level data. Interest groups will be able to more effectively combine their data in ways to make their community's case.

4.1.8 Risks and Challenges

The biggest challenges are:

- First and foremost, creating the incentives to initial data providers to engage and open up the personal data APIs that are needed to fuel the PDS and associated applications. This is a standard first mover problem: until there are such data, the app developers cannot engage; and until there are engaged app developers, the utility of the data is minimal. Moreover, some business models may feel challenged by the accessing of data by their subscribers either because they feel it discloses performance issues in their services, or they are concerned about other third parties from getting access to monetizable data, or they are concerned about subscriber perceptions once they see and have to carefully handle these data, or they are concerned about liability issues if data is inaccurate or processed without legitimate basis, or they are concerned that the data may allow third parties to reverse engineer algorithms that are perceived as trade secrets.
- A second challenge, both in conceptual and perception terms, arises from the confusion between data access and data ownership. That is: is it my data, or data about me? PDS may have to align with national policies and regulations.
- A third, more technical challenge, relates to creating utility from the data: data fusion, sense making, and visualization that will lead to meaningful and actionable and sustainable engagement of the end user with their data. Moreover, this utility must compete in the market with closed platform commercial alternatives that provide similar function to the end user without control over their data.
- A fourth challenge arises from the potential for PDS (and the apps that will be created to work on PDS data) to subtly influence user behaviour. Apps developed for PDS will reflect the coders' value systems (for instance, what data the coder thinks is most important to consider or use, or even what user behaviour should be encouraged or discouraged). Paternalistic or soft paternalistic interventions may reduce user autonomy. This scenario is particularly troublesome, considering that data streams and the algorithms apps will apply onto the data may not be visible to, or understandable by, the end user.
- A fifth challenge arises from the observation that it is neither obvious nor guaranteed that PDS will resolve user privacy problem. PDS, for instance, may provide users with local control over the data, but may not be able (both for technical and economic reasons) to stop third parties from collecting and exploiting user data. In a worst case scenario, PDS may even end up facilitating third parties' collection of user data, by creating a central repository for the user's diverse data streams.
- A sixth challenge arises from the fact that data aggregated in the PDS may be accessed and used against the user's interest (and potentially without her knowledge) for the purpose of law enforcement or other governmental use. It may also be subject to discovery in civil lawsuits. Even without legitimate reason, individuals may be more likely to fall for trickery or coercion than third parties who routinely handle requests and know the conditions under which they have to comply.
- The PDS architecture itself represents an important challenge in terms of storage, processing and security:
  - Storage of data must be flexible to accommodate local, hosted and cloud based alternatives.
  - Processing: providing the flexibility of local processing, simple APIs for third party application developers, and flexibility as to where accessed and derived data are actually stored (locally, hosted, cloud). Some processing services will be real-time and some more offline and retrospective; both modalities need to be supported.

- Security of the PDS itself, in terms of key management, audit mechanisms, and robustness (avoiding single point of failure and vulnerability to mobile device loss/theft/damage).
- Security of third party data extraction APIs to grant access only to the PDS of authorized users. This is particularly challenging if the user is only weakly identified or data refers to more than one user.
- Security architecture of the PDS app platform with regard to granular and usable access permissions and the suppressions or detection of covert channels.

4.1.9 Conclusions

We discussed the notion of a Personal Data Service (PDS) as a trusted container for aggregating, storing, processing and exporting personal data. By considering a household and a health related scenarios, we identified some of its properties and functionalities and sketched a possible architecture including such a container. Our discussion of benefits and risks shows that there are still several issues to be investigated including privacy and security aspects, and real challenges need to be addressed before a PDS framework can be implemented and deployed.

4.2 Social Justice

Mads S. Andersen (Aarhus University, DK)
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Ioannis Krontiris (Goethe-Universität Frankfurt am Main, DE)
Sören Preibusch (Microsoft Research – Cambridge, GB)
Martina Angela Sasse (University College London, GB)
Katie Shilton (University of Maryland – College Park, US)
Sarah Spiekermann (Universität Wien, AT)

This working group explored the idea that privacy issues in participatory sensing are symptoms of broader concerns about the impact of sensing on social justice. Framing a social justice research agenda for participatory sensing challenges us to operationalize concepts like fairness, human flourishing, structural change, and balances of power for system design, use, and regulation. We discussed how we might begin to operationalize these concepts for the design of data collection features, processing, sharing, and user interfaces. We developed an analysis tool – a social justice impact assessment – to help system designers consider the social justice implications of their work during the design phase.

4.2.1 Definitions of Social Justice

We first began with a discussion of definitions of social justice. We drew primarily on the work of John Rawls [3] and Amartya Sen [4]. Rawls wrote that we could best achieve a just society by setting rules that anyone would agree would be fair from behind a "veil of ignorance," in which no one knows where in that society they will be placed. Sen wrote that justice requires that individuals have the basic capabilities (education, health) they need to flourish and make the most of their lives.

4.2.2 Domains Impacted By Ubiquitous Experience Sharing and Participatory Sensing

We next discussed a variety of social domains in which we believe justice will be impacted – positively or negatively – by ubiquitous information sharing.

On the positive side, we believe that ubiquitous sharing platforms hold great promise for leveling the playing field in a variety of social domains. It seems clear that participatory sensing will have a positive impact on health, as patients are empowered with respect to institutions and new forms of data enable new kinds of diagnosis, monitoring and treatment. Similarly, care and independent living support for older citizens may be positively impacted by increased experience sharing. Sensing might even be useful for improving psychological health and mindfulness. We discussed whether context-aware applications might even be helpful for pursuing personal virtues, such as honesty or generosity.

On a social level, we think ubiquitous sharing can benefit community integration through applications like neighbor-to-neighbor sharing of goods, services, and experiences. We discussed scenarios in which ubiquitous experience sharing could benefit food systems and reduce waste by connecting producers more directly to consumers. Sensing can enable mapping of citizen's relationship with cities, as projects on walkability, bikeability, and even the emotions evoked by places demonstrate.

Sensing might also help us improve environmental justice, for example by helping communities make the case about unequal air pollution levels in underserved communities. Citizens armed with sensors might be better equipped to surface inconvenient truths about quality of life in their neighborhoods, and provide the impetus for like-minded individuals to start talking, and proceed to other organized responses to achieve change ("unionization" of citizens and consumers). Finally, we discussed a number of ways that experience sharing and participatory sensing (or "sousveillance") can increase transparency and accountability of powerful organizations to the citizen. Poll watching (such as that performed using mobile phones by Ushahidi) and cop watching [1] are two practices in which phones are used to keep governments accountable.

More complicated scenarios included sensing's impact on community rules and enforcement. We discussed digital vigilantism, and whether it could empower local communities or lead to increasing conformity and stigmatization. It is not yet clear under which circumstances "peer to peer" infrastructures for policing social norms increase or reduce justice. Education is another social context in which the impact of sensing is unclear. Sensing programs such as Mobilize[1], which use participatory sensing to teach data literacy in underserved communities, hold promise for improving justice in the educational systems of data-intensive societies. Sensing could conceivably increase accessibility for children with some types of learning challenges. But will these measures benefit underprivileged communities, or already well-resourced schools? And will participatory sensing also allow for increased monitoring and measurement, further quantifying student learning outcomes and potentially enabling stigmatization and pressure for conformity?

Criminal justice is another area in which ubiquitous information sharing is more likely to produce greater inequalities than less. We've already seen the tracking of sex offenders after serving out a prison sentence made easier by technology, and it's not hard to imagine apps that would help citizens avoid all contact with former inmates. What does this do to the concept of rehabilitation and a "second chance"?

[1] http://www.exploringcs.org/about/related-grants/mobilize

Participatory sensing also raises the specter of increasing inequality in a variety of social sectors that involve profiling and demographic sorting. Previously, indicators such as skin color, gender, etc. were used to sort people into categories. With increased sensing capabilities, will we see the emergence of new marginalizations, new visibilities, and new indicators? With sensing, you can "see" so much more. Will those factors be used to divide and discriminate? For example, we discussed possible negative impacts on the insurance industry. The current trend in insurance is away from spreading the risk among a population, and towards profiling to quantify individual risks. Participatory sensing data ranging from driving habits to location-based indexing of environmental data could all increase the granularity of personal profiles. Similar sorting could impact the financial industry, risk management, and price discrimination (charging different prices based on the ability to pay).

In cases of social sorting (such as price discrimination), research has shown that people tend to find such sorting fair provided they can understand the system behind the sorting. With ubiquitous sensing, we accumulate piles of big data for mining. New characteristics emerge, which are used as proxies for willingness to pay, health risk, etc. These new categories may be perceived as unfair if they are difficult to understand. Indeed, the complexity of the algorithms used may be beyond explanation to non-statisticians and machine learning specialists.

4.2.3 Contribution: A Social Justice Impact Assessment

After this high-level discussion, we decided to construct a method for drilling down on specific applications to evaluate their potential impact on social justice. We discussed the factors we would need to make these classifications, including such questions as:

- Who is the target of the data collection? (Individuals, groups, things?)
- Who collects the data? Who analyzes it?
- What is the intended goal of the application?
- What forms of feedback are given (motivating vs. punishment)?
- Is the data aggregated?
- How distributed is control over the data?
- Are incentives given? Financial? Is the data collected with or without knowledge or consent?
- Who might be caught up or implicated without knowledge or recourse? Are there negative externalities to data collection?

Using these questions as a loose guide, we built on earlier assessment techniques suggested by Oetzel and Spiekermann [2]. The scenario of neighborhood sensing was chosen to exemplify a social justice impact assessment: users would contribute air quality data and self-reports of issues like allergies and asthma to challenge a city's existing air quality models.

The first step was to break the concept of "social justice" into smaller component parts. The group listed:

- Fairness
- Flourishing
- New opportunities
- Structural change
- Power Dynamics
- Plurality / diversity

We next chose "fairness" to break into even further sub-components (in a comprehensive assessment tool, a similar exercise would be carried out for each of the other five components). We defined these as:

- Equality
- "Just desserts" (meritocracy)
- Distributive justice
- Chance to reply
- Procedural justice
- Transparent processes

We then set out to see how each of these smaller concepts might impact the case of a neighborhood sensing application which included a location tracker to index a person's personal environmental impact, crowd-sourced measures of air pollution, crowd-sourced data about the state of roads, and self-reports of asthma rates. Again focusing on the first sub-component, we asked: how could the neighbor sensing app threaten equality? We identified threats (T's) including:

- T1: Distortion of facts leading to unequal funding
  - T1.1: Analysis done in a biased way
  - T1.2: Creation of biased samples
- T2: Indirect negative externalities to individuals
- T3: Direct negative externalities

We then identified control or mitigation strategies (C's) that could be built into the application.

- C1: Make raw data available (T1.1)
- C2: Statistician ensures the representative data sampling (T1.1)
- C3: Analysis algorithms should be published for scrutiny (T1.1)
- C4: Collect data that allows for meaningful transparency (T1.2)
- C5: Privacy controls (T2)
  - C5.1: Anonymization (and aggregation?) of individual data (T3)
  - C5.2: Giving the individual the choice to participate (T3. Influences T1.2, so a tradeoff exists)

4.2.4 Open Questions

During the course of the work, we identified several open questions that could spark future research. These include:

- If we assume that participatory sensing will lead to greater transparency, will such transparency equally impact individuals, powerful people, and institutions? For instance, should powerful officials or celebrities be subject to the same transparency needs as institutions?
- Do the powerful always end up subverting transparency schemes? Or can sensing change that tendency, for example by making facts visible to consumers and citizens, enabling organized responses (unionization)?
- When thinking about individual liberties vs. social action, does sensing technology push in one direction or the other? As someone nicely put it: "Ask not what sensing can do for you, but what sensing can do for your country."

- What are the forums for encouraging collective action in participatory sensing? Can we encourage system designers to consider social justice during design by framing design as a collective action problem? Can participatory sensing open new avenues for consumers and citizens to organize collective action?
- Could sensing data help us "diagnose" people's moral predispositions? (And therefore political behavior?)
- What factors in sorting and categorization processes make people feel that resulting algorithmic treatment is fair or unfair?

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4.3 "Tool Clinics" – Embracing Multiple Perspectives in Privacy Research and Privacy-Sensitive Design

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4.3.1 Focalism – The Challenge

Computer scientists or engineers are continually asked to "solve problems" or "improve" existing situations, by selecting from available design features to produce the "best" technical solution. For example, a software developer faced with the problem of securing data must choose between different encryption algorithms – each with different characteristics. Factors such as strength of encryption, speed of encryption, usability, key management and hardware requirements must all be considered. Other requirements such as the sensitivity and amount of data to be protected, the estimated resources of potential attackers, the operational context of the required solution, etc. must also be taken into account. It is impossible for any solution to be 100% perfect, e.g. encrypting data with no detectable delay using an algorithm which cannot be broken. Trade-offs during the design and development process are therefore inevitable as requirements are balanced, e.g. speed vs. strength of encryption. These trade-offs are dilemmas faced by the specialist in arriving at the final design. However, what is the "best solution", and who decides what "best" means, requires more involved discussion and reflection. The engineer, with their narrow focus on solving the technical problem, might not be best equipped to solely decide what the optimum solution is, particularly if there are likely to be unintended consequences when the solution is deployed, or the proposed technology is decoded differently by users, those directly or indirectly affected, and other stakeholders.

The desire of specialists – particularly those in the fields of science or technology – to frame complex and messy situations as a single problem to be solved by technology – for which only they have the answer – often leads to overconfidence in the envisaged solution, an overemphasis on intended consequences, and a tendency to focus narrowly on one or a few aspects of the problem. This is typically identified as a form of "technological determinism", a perspective which consists of two parts: (1) the belief that technological developments take place outside society, independently of social, cultural, economic and political forces; and (2) the assumption that technological change causes or determines social change [31]. This kind of technologically deterministic approach can result in bigger problems than the one originally being solved because the understanding of the original problem situation was incomplete or wrong; Tenner [26] calls these the "unintended consequences" of technological innovation, e.g. the increasing resistance of certain strains of bacteria to antibiotics. However, unintended consequences are not restricted to technological innovation, but occur in political science, organisations, medicine and public health, ecology and social systems [11, 26]. Ehrlinger and Eibach [11] observe:

> "*[F]ocalism, or a tendency to focus narrowly on one or a few variables, [...] with respect to the intended consequence can result in a neglect of important information regarding alternative, unintended consequences – including information that is knowable and plainly relevant to predictions*" (p. 60)

Using a computer simulation, Ehrlinger and Eibach [11] showed that participants who were "defocused" by being encouraged to consider a wider system of variables, tended to make more accurate predictions and were less optimistic about the proposed solution. This suggests that viewing problems more holistically – particularly from multiple perspectives – can improve decision-making and increase the chances of successful technology development. Focalism – probably first suggested by Wilson et al. [30] – is essentially the same as "focusing illusion" proposed by Schkade and Kahneman [21] and Loewenstein and Schkade [14]. They found that when people are asked to predict their emotive reaction to a major event (e.g. the loss of employment), they typically concentrate on their likely responses to the focal event, to the exclusion of possible effects of other non-focal events (e.g. new opportunities to start a business or retrain). A practical example of people's tendency to ignore other events when their attention is focused elsewhere – inattentional blindness – is described the study by Simons and Chabris [23] in which most people missed a gorilla appearing during a video, when asked to concentrate on the number of times the ball was passed between particular basketball players.

We propose that the notion of focalism is equally applicable to scientists and technologists, who are often reluctant to challenge assumptions surrounding a problem, and principally concentrate on finding a solution to the problem as they perceive it, without adequate consideration of: (1) what it is that actually needs to be achieved – not from only one viewpoint; (2) any foreseeable consequences of the proposed solution; (3) and the viewpoints of other affected and/or interested actors who may have different priorities. We suggest this can be viewed as "solution focalism", and we propose that de-focusing may best be achieved by making other viewpoints salient As Genus observes, "*the employment of participatory approaches has been proposed to accommodate the interests of a wide range of actors holding different value positions, while minimising the potential risks associated with technology development.*" [12]

The problems of focalism are not restricted to technology development. It also reduces the efficacy of privacy research and privacy-sensitive design. For example, Privacy Enhancing

Technologies (PETs), such as Privacy Bird and Privacy Finder[2], appeared *prima facie* at the time to offer useful technical solutions to the problem of managing people's privacy. Both PETS use a protocol published in 2002 by the Platform for Privacy Preferences Project (P3P) [7] that enables web sites and applications to describe their privacy policy in XML. However, they have failed to become widely accepted and deployed. In 2003, the adoption rate of P3P was broadly flat at around 10% [10], partially due to the limited functionality of the first P3P user agents, and user interface problems [8]. Reay et al [18] observed that "*P3P adoption has stagnated in a niche position; it appears that browser implementers simply do not have enough market incentive to expend the resources needed to develop and integrate P3P 1.1 user agents*" (p. 162). Those browser implementers that did implement P3P made such fundamental technical mistakes that P3P was easily circumvented by publishing invalid policies [9]. Companies who chose not to use P3P suffered no consequences, which underlined the fact that P3P – albeit an elegant technical design – also required, as a minimum, enforcement external to itself, either through government regulation or industry self-regulation, both of which never materialised. The development of P3P may have benefited from collaborative design and development informed by a critical assessment of the perspectives of browser developers, the interests and technical capabilities of those who host and manage web sites, and the role of regulators. Certainly, there is much to be learned from the P3P experience that can be used to look at contemporary proposals for privacy-sensitive design. Focalism has also influenced the empirical aspects of privacy research. Many privacy studies have focused on the user experience with different interfaces and privacy controls, without thinking more holistically and considering the context in which the tool is used, the primary goals the user is trying to achieve, or the interaction of these goals with the interests of other affected stakeholders.

We propose a "tool clinic" to encourage a collaborative (re)consideration of a technological solution, research technique or other artefact, in order to critically assess its design, development and deployment from multiple perspectives. Another objective is to turn such solutions or artefacts into a tool for exploring the problem space. For example, what is the privacy problem when we look at it through a solution such as P3P? Finally, a tool clinic can be used to provide those who are developing the solutions with a setting to rethink the framing and presentation of their solutions. The term "tool clinic" emphasizes the motivation for embarking on this exercise. Athletes dedicated to improving some specific skill routinely go to a "rebound clinic" (in basketball) or a "dribbling clinic" (in football). The use of the word "clinic" does not indicate that a tool clinic provides a specific fix for problems, best practice guidelines, or solution templates – a typical panacea sought by those in the field of engineering. Rather, a tool clinic provides a framework and approach for multiple-perspective formative exploration and review of a technological solution, research technique or other artefact under development. The objective is to reflect from different perspectives on practices around the development, encoding, use, domestication, decoding and sustainability of a tool to gain quasi-ecological validation. In this sense, a tool clinic is more like a "law clinic", where law students study law and practice the adversarial legal process in context, or "design crits", during which designers learn to critique and receive critique of their work from others in the arts, academia or design practice.

[2] Privacy Bird was initially developed by AT&T. Privacy Bird and Privacy Finder are managed by Carnegie Mellon University's Usable Privacy and Security Laboratory.

4.3.2 Existing Uses of Multi-perspective Formative Exploration and Review

It is important to demonstrate that similar approaches to the suggested "tool clinic" are already used successfully in areas of industry and academia. This section describes some existing techniques that use a multi-perspective and collaborative approach.

In industry, disaster recovery practitioners often use corporate "war games" – a term originating from the military – to simulate a potential disaster situation (e.g. the loss of a data centre), and step through its disaster recovery plans to ensure they operate correctly. This avoids situations such as employees not being able to relocate to a cold-standby office building due to keys or swipe-cards not being readily available because the security department was excluded from disaster recovery planning. The use of disaster recovery simulations involving all affected areas of the business ensures disaster recovery plans are considered from multiple perspectives. A related technique to war games, the "Red Team"[3] review, also originated in the military as a means of assessing plans in an operational context from the perspectives of adversaries, affected areas of the military and their partners. Like war games, a Red Team review subjects a problem, plan, process, technique or artefact (e.g. tool, document, service, software product, etc.) to rigorous scrutiny by trained team members and experts. One of the authors of this report has been involved in Red Team reviews of complex commercial bid documents by the technical design and implementation, financial, service management and legal areas of a business organisation.

Gaining multiple perspectives is a technique also used by Soft Systems Methodology (SSM), which emerged in the 1980s from Checkland's work [5, 6]. SSM is a framework for organising the exploration of messy, complex problems as a learning *system*, and therefore failures in projects, processes etc. are viewed as a *systems failure*. Checkland [5] suggests that to fully understand a system it is necessary to consider its purpose from different viewpoints. This systemic pluralism represents one aspect of the "soft" systems approach, which aims to construct a rich picture of a problem, encompassing different viewpoints, rather than the reductionist focus of systems engineering. These different viewpoints, or *Weltanschauungen*, represent unquestioned models of the world that makes the system meaningful for study [5, 6]. It is important to stress that although SSM views problems as a *system*, it is not a representational model of reality; it is epistemological, not ontological; just because SSM views a situation *as if it were* a system, does not mean *it is* a system [6], e.g. a computer system.

To facilitate understanding of the reasons for failures, Checkland created the idea of a *formal system model* (FSM), which is a "*general model of any human activity system*" [5]. Comparison between the formal system model and the conceptual model of the problem situation under investigation is an intrinsic part of the SSM process, as it identifies flaws, weaknesses and omissions in the conceptual model, facilitating its improvement. The improved conceptual model can be compared with the real-world situation to determine which desirable or feasible changes are required [5, 6]. A project specific form of the FSM has been developed by Fortune et al [28] for use in analysing project failures, such as large-scale building projects [29].

The existing multi-perspective techniques described thus far, not only subject items to rigorous review, but encourage collaborative improvement and design. Soliciting the

[3] A "Red Team" is defined as "a team that is formed with the objective of subjecting an organisation's plans, programmes, ideas and assumptions to rigorous analysis and challenge. Red teaming is the work performed by the red team in identifying and assessing, inter alia, assumptions, alternative options, vulnerabilities, limitations and risks for that organisation." [1].

viewpoints of stakeholders, potential users of a technology or service, and those affected by it, can dramatically improve its quality. The notion of collaborative development and improvement to ensure effort is not expended on features or services that customers do not require, is key to the notion of "*the lean startup*" [19] used by many Internet companies. The lean startup philosophy suggests that companies release a "minimum viable product" – a "*version of a new product which allows a team to collect the maximum amount of validated learning about customers with the least effort*" [19] – to a subset of sympathetic customers, such as early adopters. The release of a minimum viable product is part of an iterative prototyping process, collecting suggestions for improvement, learning how customers use the product and what they want from it. The use of minimum viable products allows business to understand how customers actually decode the technology or service being provided; the product must be viable in that the customer must value what it provides. Use of minimum viable products should be an iterative learning process, generating ideas and collecting data about product use.

One existing approach to answer the question posited earlier, "*Who decides what 'best/better' really means?*" is constructive technology assessment (CTA). The latter fits within the long-standing tradition of Science and Technology Studies (STS), which investigates how the things that it studies are being constructed. The STS domain has increased its scope over the years, starting with scientific knowledge and expanding to artefacts, methods, materials, observations, phenomena, classifications, institutions, interests, histories, and cultures [24]. One of the most prominent ways to apply the thinking in STS in the real world has been the CTA approach. The objective of CTA is to "*produce better technology in a better society*" [12] by taking a more social constructionist position, and moving "*beyond technological determinism towards an evolutionary view of technology development*" [12]. This is done by advising on interventions in early stages of technology development based on the assessment of possible problems and risks that these technologies could pose for society [25]. CTA emphasises the importance of including a wide range of actors to anticipate the potential impact of a technological development ("vermaatschappelijking" of technology [27]) and decide on improvements to it, thus facilitating social learning. It should be stressed that CTA is not a research method, but an overall approach into which participatory techniques may be placed. Genus [12] suggests moving away from the interventionist and prescriptive stance of existing CTA approaches towards a more discursive, democratic and reflective process because "*contention and openness to criticism are prerequisites for producing reflective socio-technical expertise*" [12]. This is also known as "participatory technology assessment" [13]. The use of a modified form of CTA to address the ethical problems caused by technology is proposed by Palm and Hansson [16] as part of a continuous dialogue between developers and affected actors. For emerging technologies, Merkerk and Smith [27] propose a three-step CTA approach, using permutated dialogue workshops attended by insiders and outsiders to the item under review to consider selected issues about the proposed technology and reflect on different technology scenarios.

In order to apply multi-perspective formative exploration and review of technological solutions or tools in early stages of development, different types of multi-method approaches have been developed. One of the most elaborate ones is the living laboratory approach. The 'living lab' is a specific type of test and experimentation platform (TEP), which refers to facilities and environments for (joint) innovation including testing, prototyping and confronting technology with usage situations [3]. Living labs are facilities for designing, developing, testing and evaluating communication technologies and services in early stages of the innovation process. They do so by involving (early) users, in line with the CTA

perspective. However they can also be configured as open and innovation-oriented platforms that involve various technology experts, disciplines and/or stakeholders in different stages of technology design, development and testing [17]. Thus, we discern three main ways to put living labs[4] into action as: (1) a platform for open innovation; (2) a user-driven research methodology; and (3) an experimental setting [20].

4.3.3 Perceived Research Gap in Privacy

Most privacy researchers agree that privacy is contextual and dependent upon information use, information sensitivity and the trust in the entity collecting, storing, processing and disseminating the information entrusted to it [2]. Furthermore, users engaged in technology mediated interactions with other parties will have expectations and assumptions about the technology, the providing organisation and other partners in communication [2]. If these assumptions and expectations are violated, the user is likely to have an emotional reaction and reject the technology and/or providing organisation [2]. A practical example of this was the launch of Google Buzz. Gmail users believed they were only signing onto Gmail as usual, when they were actually being enrolled in Google Buzz [22]. It would appear the developers of Buzz did not take into account: (1) that people's primary task was to access their e-mail and hence they would likely "swat away" any dialogue boxes without properly reading them; and (2) that people's mental model is that Gmail is a tool to access their e-mail and not a social networking service.

User studies may aid developers and designers in foreseeing likely troubles that users may have with a given design. However, the task of achieving an understanding of the complexity of the privacy problem, and translations of this problem into the technical solution space may benefit greatly from a multi-perspective approach. This is line with the notion of *contextual integrity* (CI) by Nissenbaum [15], which is used to answer whether a situation contained a privacy breach or not. CI is guided by norms of appropriateness (i.e. norms that govern what can be disclosed in a certain context or situation) and norms of distribution (i.e. norms which assess the transfer of personal information from one party or context to another context). This demonstrates how not all publicly revealed information or information collected in the public space, is meant for every form of public use. "*Just because something is publicly accessible does not mean that people want it to be publicized. Making something that is public more public is a violation of privacy.*" [4]

Addressing the privacy implications of increasingly complex, powerful and ubiquitous computing will be even more of a challenge than Buzz, as the potential for unintended consequences is even greater than before. However, privacy researchers and practitioners continue to work largely in isolation, concentrating on people's use of different user interfaces for privacy control, and have largely ignored existing cross-disciplinary collaboration techniques such as those described above.

4.3.4 Future Directions for Researchers and Practitioners

Tool clinics are essentially practices, and they need to be living practices – thus future directions are not only researching, but also must be *doing* tool clinics. We have performed a first *ad hoc* requirements analysis for tool clinics at the Dagstuhl Seminar itself (i.e. we "clinicked"

[4] In Europe living labs are associated in the European Network of Living Labs (ENoLL) which was set up under the auspices of the Finnish EU presidency in 2006 and since the 6th wave of call for new members in March 2012 consists of over 300 accepted members.

the tool clinic idea) and have seen the challenges the concept poses. Most importantly, our clinic participants expressed concerns about exposing their methods, approaches and original ideas to a critical audience. Further issues were raised with respect to matters of intellectual property. Some of these problems are likely to stem from the employment requirements and the working conditions of senior and junior researchers. They also often associated the word "clinic" with doctoring their (software) artefacts with others, a goal that we only partially share.

Based on this experience, our next step will be to develop a tool clinic as a new event format for a scientific conference, ideally at a renowned computer-science conference. This will combine the tool-centric nature of a demo session, the protected space of work-in-progress afforded by a workshop, and the mentoring spirit of a doctoral workshop[5].

The format of a tool clinic session could typically consist of three steps (inspired by the CTA and Privacy by Design approach):

1. Identifying particular affordances of the technological solution, research technique or other artefact and possible (unintended) consequences for people and society;
2. Gathering perspectives and practices of different experts, disciplines and/or stakeholders (e.g. users, policy makers, industry, etc.) linked with the development, deployment and sustainable evolution of a particular tool, solution, technique or artefact;
3. Informing and advising on technological design of the tool or solution, in order to avoid negative consequences and to further positive outcomes.

We foresee three essentially needed incentives for participation: (1) enlisting big names in the field who can signal through their own example that "grown-ups too can learn"; (2) a broad-enough team of participants to represent a wide range of perspectives; and (3) a follow-up that makes it worthwhile to put oneself into the ring. For the first two, we can draw on our respective scientific networks. A special issue in a good journal is one option for creating the third incentive, and further developments of the tool clinic method described in the introductory article of this special issue are among the next intended research activities.

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4.4 Consequence-based Privacy Decisions: a New Way to Better Privacy Management

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4.4.1 Introduction and Motivation

An increasing number of users contribute privacy-sensitive content, such as pictures, comments, or location information, to online services. In order to protect the privacy of the users or to comply with data protection regulations, most services enable the users to customize privacy and sharing preferences. For example, this includes determining who will be authorized to access or receive and process which content and for which purposes. However, management of privacy preferences is often a fairly complex procedure that even technically savvy users often fail to understand.

Recent research shows that people would like to control their privacy and actually do so. For example, the number of Facebook users with customized privacy settings has been growing in the last years. However, users are frequently unaware of consequences resulting from their selected configuration and cannot be sure that the changes will actually have the effects they are intended to have. In addition, many users do not set or adapt privacy settings as they cannot correctly grasp the consequences of their actions. For instance, tagging a person on a photo may cause this photo to appear in searches of this person, which may be at time unwanted. Although recently some tools for granular privacy management emerged, the problem of determining all the consequences at the system level and showing them to the users in an understandable and actionable way still remains largely unsolved.

We argue that an appropriate privacy-respectful user interface should show users the consequences of making different privacy choices, rather than framing the choices only in technical terms regarding system parameters which users often do not understand and do not care about.

We believe that providing tools to increase user comprehension of potential consequences is one of the next big challenges to be addressed in the field of privacy respectful user interfaces. In addition to helping users to make better choices in terms of privacy protection, this will also allow them to make better informed decisions and hence, implement the notion of informed consent (that is often required pursuant to Art. 7 European Data Protection Directive 95/46/EC) not only formally but also to live up to the spirit of this legal requirement.

4.4.2 Challenges and Research Directions

The attempt to develop user interaction regarding privacy in which the user is clearly aware of the consequences of actions requires research on a number of issues that have so far received relatively little attention:

Expression of potential consequences

Informing the users should take into account several parameters. Indeed, users may have different backgrounds and education levels. As a result, the consequences should be expressed in a way comprehensible by different user categories from novices to expert users. This may include translating potential consequences into different metrics. Such metrics do not exist at this time. For instance, if a user decides to share his/her location, the interface could display a list of people that will be able to see this location. This list could include close relatives as well as remote friends and unknown people. In the computation of relevant metrics, the context, e.g., the user's location, will need to be taken into consideration as the notion of privacy depends on the context. Finally, the consequences should be displayed in usable interfaces.

Decision support

In addition to displaying potential consequences, users could be further helped in their privacy decisions by external information sources. This could include showing the privacy decisions of their relatives, friends or other expert and non-expert users (e.g., via crowdsourcing). By doing so, users may have a social reference and make better informed decisions. On the other hand, this may influence them to disclose more sensitive data than they initially intended to disclose. As a result, studies to determine the responses to different kinds of information sources, different formats, and information from different groups of users will be necessary. For example, trade-offs between privacy and social compliance in case of crowdsourcing need to be investigated.

Minimal effort

Introducing additional tools to help users make informed decisions may add significant overhead to the interaction. While this overhead may be the price to pay for better privacy protection, it should be limited to the minimum. Otherwise users may be tempted to rush through the configuration and ignore this additional step. In this context, habituation effects are a serious problem that has to be taken into account. As a result, novel interaction schemes that are robust to such effects need to be investigated and developed to provide users with appropriate tools.

4.4.3 Activities of the Group

During the workshop the group identified the issue of consequence-based privacy decisions as a topic with great possible potential. After discussing the topic we developed a conceptual model and identified the major challenges that need to be addressed if one wants to implement consequence-based privacy decisions.

Furthermore we began to work on a joint conceptual paper, presenting the problem of users being unable to predict the implications of privacy decisions they make. The paper proposes some directions which may be taken to build a system that provides users with information about the consequences of their actions. We also discussed possible directions for future joint research resulting from the workshop. This includes organization of follow-up meetings of workshop participants and the search for possible funding sources for research, based on the ideas developed in the workshop.

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