ZEITSCHRIFT DES TELEMATIK-INGENIEUR-VERBANDES TIV

ISSN 1028-5068

Telematik 1/02

T E L E k o m m u n i k a t i o n & I n f o r M A T I K

Algorithms

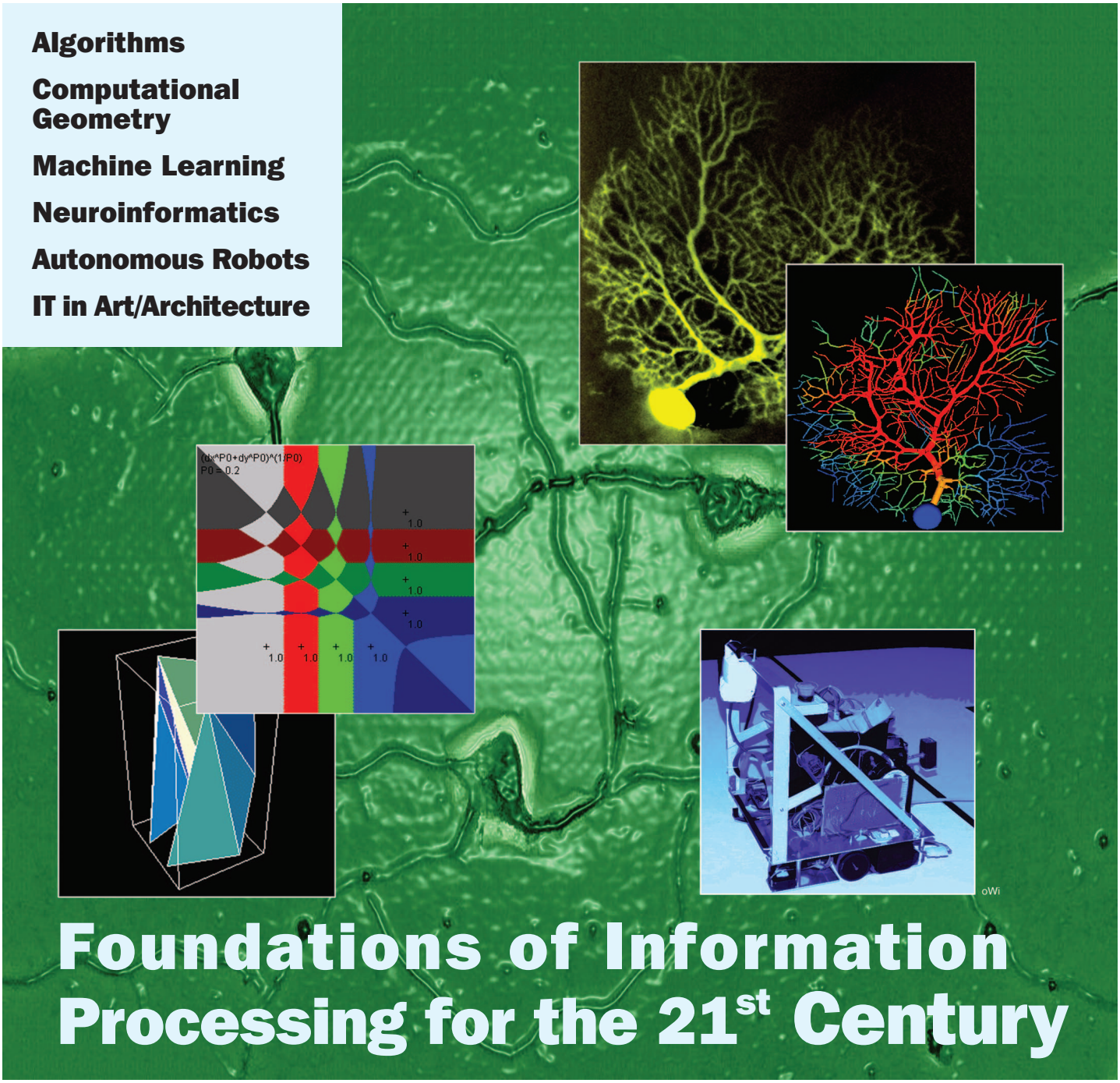
Computational Geometry

Machine Learning

Neuroinformatics

Autonomous Robots

IT in Art/Architecture



Foundations of Information Processing for the 21st Century

Verlagspostamt 8010 Graz, P.b.b. 327892G95U, Jahrgang 8, Nummer 1/2002

Inhalt

Editorial Heft 1/2002

O.Univ.-Prof. DI Dr. Wolfgang Maass
Vorstand des Instituts für Grundlagen der Informationsverarbeitung an der TU Graz

Liebe Leserinnen und Leser,

aus Anlaß des 10-jährigen Jubiläums des Instituts für Grundlagen der Informationsverarbeitung der Technischen Universität Graz im Frühjahr 2002 widmet sich dieses Heft den Kernthemen der Forschung an diesem Institut: Algorithmen, Maschinelles Lernen und Neuroinformatik. Aufsätze von Mitarbeitern des Instituts sowie einigen auswärtigen Forschungspartnern geben allgemeinverständliche Einführungen in diese Forschungsgebiete, sowie Einblicke in gegenwärtig aktuelle Forschungsprobleme. Am Schluss des Heftes finden Sie eine Liste der Publikationen unseres Instituts, von denen die meisten über http://www.igi.tugraz.at online erhältlich sind.

Ich möchte allen Autoren dieses Heftes herzlich für ihre Beiträge danken, insbesondere unseren auswärtigen Forschungspartnern Prof. Nicolò Cesa-Bianchi von der Universität Mailand, Dr. Hans Diebner, Abteilungsleiter am Zentrum für Kunst und Medientechnologie (ZKM) Karlsruhe, Prof. Rodney Douglas, Direktor des Instituts für Neuroinformatik der ETH und Universität Zürich, Prof. Philip Long vom Genome Institute in Singapur, Prof. Henry Markram, Direktor des Brain Mind Instituts der Ecole Polytechnique Federale de Lausanne (EPFL), Prof. Kevan Martin vom Institut für Neuroinformatik der ETH und Universität Zürich, Prof. Peter Weibel, Direktor des Zentrums für Kunst und Medientechnologie (ZKM) Karlsruhe und Chefkurator der Neuen Galerie Graz und Prof. Manfred Wolff-Plottegg, Vorstand des Instituts für Gebäudelehre und Entwerfen der TU Wien.

Ich möchte ebenso der großen Zahl der hier nicht genannten Freunde und Förderer unseres Instituts im In- und Ausland, die unsere Arbeit in den vergangenen 10 Jahren ermöglicht haben, auf diesem Weg ganz herzlich danken. Ich hoffe, dass diese, aber auch alle anderen Leser, Freude haben beim „Schmökern" in diesem Special Issue von Telematik.

Ihr Wolfgang Maass

Titelbild: *Oliver Friedl, Institut für Grundlagen der Informationsverarbeitung, Technische Universität Graz*

Foundations of Information Processing for the 21st Century

Wolfgang Maass
Institut für Grundlagen der Informationsverarbeitung
Technische Universität Graz

In spite of its great success, computer technology of the 20th century has left many dreams unrealized. One example is the dream to build truly intelligent autonomous systems that learn from their experience and require less programming and debugging. Another one is the dream to build computers that communicate with us through direct sensory interaction. We have learnt that the solutions of these problems require deeper insight into the capabilities and limitations of computer algorithms than we currently have. Also a machine that learns needs to be endowed with efficient „learning algorithms". Such learning algorithms are implemented in most biological organisms, but computer scientists and all other scientists have been irritated for several decades by the difficulty to understand the completely different strategies of information processing and learning that nature has chosen for its own information processing devices, such as for example the human brain. Finally, computing machinery is permeating all aspects of our culture, including the artworld, offering new opportunities for creative activity that we may not even have grasped yet.

There are indications that tremendous progress will be achieved during the 21st century in all of these areas, and that this new insight will change not only the way how we build computers, mobile phones, and cars, but also the way we live and think about ourselves as human beings. Some of this progress will result from economic pressure in a competitive computer market, since the customary doubling of the computation speed of CPUs every 18 months, which has been a primary incentive for new computer products, is expected to slow down and finally come to a halt in 15-20 years, because hard physical limits will be reached. From that point on, further progress in computation speed requires the solution of some fundamental problems, such as an automatic collaboration of millions of processors on a computational problem without the nightmare of having to program and debug the protocol for this interaction. In addition there exists substantial evidence that the reason why computers and robots have not become as intelligent as we had hoped, are caused by our insufficient understanding of the true nature of intelligence, sensory perception, and cognition. Therefore computer science will not only have to continue and deepen its interaction with mathematics, but also has to establish new links to cognitive science and neuroscience.

The task of our Institut für Grundlagen der Informationsverarbeitung (Institute for the Foundations of Information Processing)[1] of the Graz University of Technology is to contribute – in close collaboration with our colleagues in other countries and disciplines – towards the development of computer science into a mature science, that provides systematic and successful tools for solving the fundamental problems that I have sketched. In particular we have the task to teach our students the most promising scientific results and tools, those which they are likely to need in order to strive intellectually and economically in a highly dynamic environment where today's newest wisdom in computer software and hardware tends to look like an old fad 3 years later. Curiously enough, our institute is the only Institute for Foundations of Information Processing in all of Austria, which increases our responsibility. Unfortunately it is a very small institute, with just 2 positions for Professors and 3 positions for University Assistants (which are fortunately supported by a great staff, and junior researchers funded by the FWF and the Österreichische Akademie der Wissenschaften). Nevertheless the scientific publications of this institute have already been cited in more than 1155 scientific publications of researchers in other countries.[2]

In this issue of the journal Telematik you will find short introductions and illustrative examples for some of the research topics on which our institute has worked during its first 10 years, since it was founded in 1992. The first article *Algorithmic Fun: Abalone* gives a playful introduction to algorithm design, which is one of the primary research areas of our institute. The subsequent two articles on *Voronoi Diagrams* and *Points and Combinatoris* provide insight into fundamental tools and problems of computational geometry, an important research area where one designs efficient algorithms for geometry-related problems. This research area, which provides algorithmic tools for computer graphics, computer vision, robotics, and molecular biology, presents a nice example for the close interaction between mathematics and computer science that is typical for most work on the Grundlagen der Informationsverarbeitung.

1 Usually the German name of our institute is translated more freely as „Institute for Theoretical Computer Science", because theoretical computer science is that branch of computer science that traditionally is most often associated with the solution of fundamental and hard problems. However during the last decade the boundaries between theoretical computer science, artificial intelligence, neuroinformatics and computational neuroscience have started to become less significant, because very successful research in any single one of these areas often involves a combination of methods from several of them.

2 Source: Public computer science research index http://citeseer.nj.nec.com/allcited.html. The number given is the sum of the citation numbers for Auer, Aurenhammer, Maass (only citation numbers for researchers with more than 147 citations are listed in this online databank).

The subsequent group of articles on machine learning presents both typical application domains (*Fingerprint Matching, Autonomous Robots, Bioinformatics*) and fundamental theoretical questions that arise in this area. The article on autonomous robots describes the current efforts at our university to build the first Austrian team of fully autonomous robots to compete in the international robot soccer championship RoboCup. The article *Why Students Don't Ask Questions* provides an introduction to mathematical models for active and passive learners, and presents quantitative results regarding the benefits of active knowledge acquisition. The article on the *Exploration-Exploitation Dilemma* presents mathematical results on strategies for balancing exploration and exploitation in a stochastic environment.

The next group of articles provides an introduction into the areas Neuroinformatics and Computational Neuroscience, where tools from computer science are used to gain insight into computation and learning in biological neural systems, both in order to solve fundamental problems of neuroscience and in order to extract new techniques for building more efficient artificial computing machinery. The article *Computing with Spikes* introduces the foreign world of computing in biological neural systems. The subsequent article on *Principles of Neocortical Microcircuits* presents the current state of knowledge and a conceptual framework for approaching one of the most exciting scientific research problems for the 21st century: How is information processing and learning organized and implemented in the brain? The next article on *Liquid Computing* presents joint research of computer scientists and neurobiologists on a new model for information processing and learning in biological neural systems. The article on *The Relevance of Understanding Brain Computation* discusses the role of Neuroinformatics and Neurotechnology in the larger context of Information Technology.

The new perspectives on information processing and cognition that emerge from the previously sketched work influence our culture, and stimulate new approaches in seemingly unrelated areas such as art and architecture. The article *Stimulus meets Simulus – Thoughts on the Interface* discusses theories of cognition and brain modeling from the point of view of an artist. The article *Architecture as Information-Editor* places architectural creativity into the broader context of information processing.

I think the articles of this special issue of Telematik reflect quite well the relevance and excitement of research on the foundations of information processing. ■

Prof. Dr. Wolfgang Maass, computer scientist and mathematician, Ph.D. under Prof. K. Schütte (Mathematical Logic) at the University of Munich, 1986-1991 Professor at the University of Illinois (Chicago), since 1991 Professor at the TU Graz, since 1992 Head of the Institut für Grundlagen der Informationsverarbeitung der TU Graz. Homepage: http://www.igi.tugraz.at/maass

Algorithmic Fun - Abalone*

Oswin Aichholzer, Franz Aurenhammer, Tino Werner
Institut für Grundlagen der Informationsverarbeitung,
Technische Universität Graz

Why games?

A main area of research and teaching at our institute is *algorithms design*. Loosely speaking, an algorithm is a method (technique, recipe) which transforms a given input - say a set of character strings - into the desired output - an alphabetically sorted list, for example. „Algorithm" is among the most basic notions in computer science. Beside the important role as a driving force in many fields of computing theory, as well as the countless practical applications, algorithms bear inherent beauty, elegance, and - fun. This may have been the motivation for many theoreticians to constantly contribute to this area. The present note, however, is not intended to present our research publications on algorithms design but rather shows that, in collaboration with students, projects of manageable size can provide all at the same time: teaching of ideas and concepts, fun, and improved results.

For half a century, board games (like chess) have often been considered as benchmark examples for artificial intelligence. Surprisingly enough, the most successful game programs to date are not really based on artificial intelligence. They mostly rely on three pillars: brute force (the power of computers), clever algorithmic techniques (algorithms design), and sophisticated evaluation strategies (developed by human intelligence). Along these lines, we present an algorithm we designed for a sophisticated program playing the board game *Abalone* on an advanced level.

Several famous people in computer science have contributed to the algorithmic theory of games. To name a few whose work is related to our topic, the fundamental principle of minimizing-maximizing strategies for games (described below) was invented by Claude E. Shannon around 1950. In 1975 Donald E. Knuth and Ronald W. Moore investigated the expected performance of alpha-beta pruning. Last not least, the mathematician Emanuel Lasker, World Chess Champion 1894-1921, developed several games and strategies.

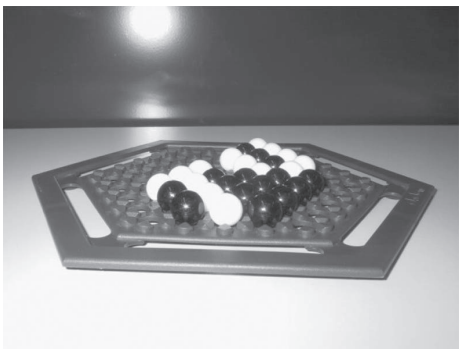


Fig.1: *Playing makes fun. Algorithms make fun. Playing with algorithms is fun*^{squared}

Abalone

Though not much older than 10 years, Abalone is considered one of the most popular ‚classical' board games. It may be the geometric appeal of the hexagonal board, the compactness of its rules, or simply the nice handling of the elegant marbles which makes Abalone an attractive game. From an algorithmic point of view, Abalone bears challenging questions. In this note, we report on a students project where Abalone[1] was chosen to implement a general search tree strategy, as well as to develop tailor-made heuristics and evaluation methods.

Rules: Abalone is played by two players, black and white, each starting with 14 balls of the respective color. The rules to move the balls are simple. If it is white's turn, then at most three aligned white balls may be moved (rigidly) by one position, choosing one of the six available directions. Thereby, black balls are pushed along if they lie in the line of movement and are in minority. Balls pushed off the board are out of the game. The goal is to be the first player that pushes out six balls of the opponent.

More details and information about this nice game can be found on the official Abalone web site at http://www.abalonegames.com.

Geometric score function

To guide the actions of the players, a means to evaluate a given Abalone constellation (i.e., a particular configuration of the balls on the playing board) is needed. As will become apparent soon, an important objective is to keep this procedure simple and efficient. The following geometric approach turned out to be surprisingly powerful. It relies on the intuitive insight that a strong player will keep the balls in a compact shape and at a board-centered position. This led us to use the static evaluation function, called *score function*, below.

1. Compute the centers of mass of the white and the black balls, respectively.
2. Take a weighted average of these centers and the center of the game board (which gets weighted with a factor below one). Call this reference point R.
3. Sum up the distances of all white balls to R (same for the black balls). Distances are measured along the six lines of movement on the board. (This is a hexagonal version of the well-known Manhattan metric.) Balls pushed off the board are granted a suitable constant distance.
4. The discrepancy of the two sums now gives the score of the position.

Minimax strategy

Abalone is a typical two-player, perfect information game. No randomness (like flipping a coin, rolling a dice, or dealing cards) is involved.

* Abalone is a registered trademark of Abalone S.A. - France

1 For other games (like Four Wins, Scrabble, ...) we developed different algorithmic strategies.

When taking turns, the two players try to maximize and minimize, respectively, the score function - from the first player's view.

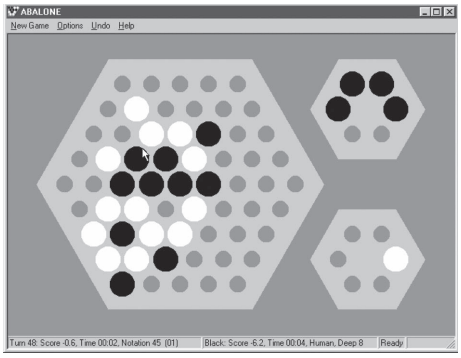


Fig.3: *Screen shot of the program.*

Accordingly, the first player is called the *maximizer*, and his opponent the *minimizer*. To figure out good moves in a systematic way, the future development of the game is represented by a *decision tree*: the branches from the root of this tree (the start situation) reflect all possible moves for the maximizer, each leading to a new game position (root of a subtree) where it is the minimizer's turn. Again, all branches from this node display the possible moves, now for the minimizer, and so on.

Suppose now that the minimizer is playing optimally. Than the best move for the maximizer will be one where the lowest score reachable by the minimizer is as high as possible; confer Figure 2. When looking ahead *d* steps, a tree of depth *d* with alternating maximizing/minimizing levels has to be considered. At the ‚end' of this tree, namely at its leaves (and only there), the score function is computed for the corresponding game positions. Then, by traversing the tree (using depth-first-search) the maximizer can find the move which is *optimal when looking d steps ahead*. Clearly, the strength of the chosen move depends on how far we can think ahead. The deeper the tree, the more critical situations, impending traps, or winning moves can be taken into account.

Obviously, in a *globally optimal* strategy there is no artificial limit on the depth of the tree. All leaves are situations where the game comes to an end. Unfortuanately, for most games this is not realistic; the tree would simply grow too fast (namely exponentially). The most powerful computers available today would not even find a first move unless we bound the depth of the tree. Still with a given bound *d* we have to be careful. The time complexity of searching the tree is roughly B^d, where *B* is the branching factor (the number of possible moves at a certain position). A quick calculation: Abalone has about 60 possible moves for a typical position, and we want the computer to calculate ahead eight moves. Provided the program can evaluate one million positions per second (which means a lot of computation plus data handling etc.) we estimate 168×10^6 seconds for one move. In other words, you have to wait over 266 years to complete a game of, say, 50 turns. Our assumptions on the computational power are still to optimistic for today's personal computers - we should multiply by a factor of 50. It is now evident that computational power will not be the key to better Abalone playing; algorithmic improvement is asked for.

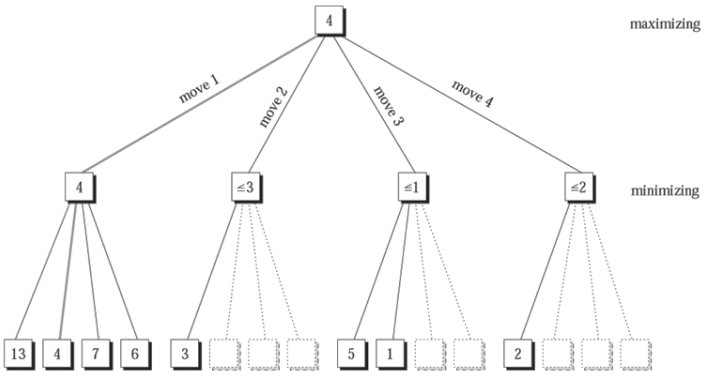


Fig.2: *A decision tree with alpha-beta pruning at work: branches and leaves drawn dotted need* not *be considered. This saves time without loosing any information.*

Alpha-beta pruning

Alpha-beta pruning is a method for reducing the number of nodes explored by the minimax strategy. Essentially, it detects nodes which can be skipped without loss of any information. Consider Figure 2 for an example. After examining the first move of the maximizer (the leftmost subtree) we know he can do a move of score at least 4. When trying his second move we find that the minimizer now has a move leading to score 3 on the first try. We conclude that there is no need to explore the rest of the second subtree: if there are moves exceeding score 3 then the minimizer will not take them, so the best the maximizer can get out of this subtree is score 3, which he will ignore since he already has a better move. In this (lucky) case we know - without looking at the remaining nodes - that no interesting move can be expected from the subtree. In this way, the number of traversed nodes can be significantly reduced.

„I think only one move ahead - but a good one!"
Emanuel Lasker, World Chess Champion, 1894-1921, when asked how ‚deep' he thinks

Technically, for each explored node alpha-beta pruning computes an α-value and a β-value, expressing the maximum and minimum score, respectively, found so far in related subtrees. With the help of these values it can be decided whether or not to consider further subtrees, because the score of a node will always be at least its α-value and at most its β-value.

Let us point out that this strategy is no heuristic at all: if the tree depth *d* is fixed, the calculated best move is independent from the use of alpha-beta pruning. The advantage lies in the number of skipped nodes and thus in the decrease of runtime. Observe further that the runtime depends on the order in which subtrees are visited. See Figure 2 again. If the minimizer first considers a move with a score higher than 4 (e.g., the third subtree) then we have to continue until a move with lower score is found. This gets particularly time-consuming if the first move of the maximizer is weak.

The best behavior will be obtained when the most promising moves (high score for maximizer, low score for minimizer) come first. It can be proved that such an *optimal alpha-beta pruning* explores about square root of the subtrees per node. (We get a complexity of $2 \cdot B^{d/2} - 1$ for *d* even, and $B^{(d+1)/2} + B^{(d-1)/2} - 1$ for *d* odd). This is still exponential in the ‚look-ahead' *d*.

Clearly, optimal alpha-beta pruning cannot be managed in real games. A simple but good approximation is obtained when treating the moves at an actual position as leaves of the tree and presorting them by score.

Heuristic alpha-beta pruning

Heuristics for playing a game try to mimic what human players do: detect all interesting situations and avoid investigation of the majority of ‚boring' moves. Usually this drastically reduces the number of work to be done, but bears the risk that tricky moves are overlooked. The ability to intuitively distinguish between strong and weak moves is considered one of the major advantages of human players over computer programs.

There exists a plethora of game heuristics in the literature, and no modern chess program could survive without them. Unlike decision trees and alpha-beta pruning, heuristics strongly depend

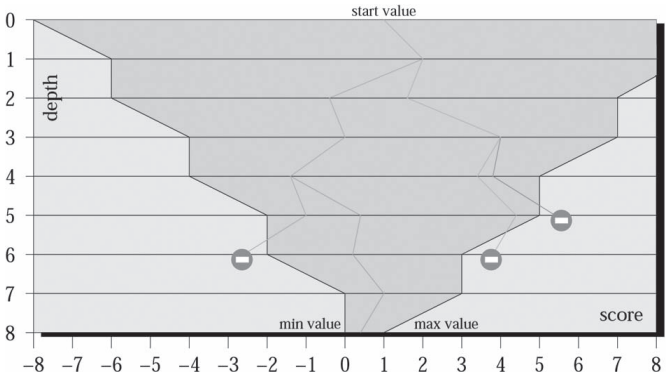


Fig.4: *The funnel of our pruning heuristic helps to bypass unrealistically bad (or good) positions.*

on the characteristics of the game in question. We found none of the popular heuristics suited well for our purposes; a new method had to be developed.

Unlike in chess, the score of an Abalone position changes rather smoothly. One reason is that all the ‚figures' (the balls) are of equal status. (For example, there are no kings which have to be protected under all circumstances.) Thus, for a reasonable move the resulting change in score is bounded, in a certain sense. This fact has an interesting implication. Assume we already have reached a very good score for a position of full depth *d*. Then we may skip a subtree of the decison tree whenever the score at its root is low (according to the above mentioned bound) and thus destroys the hope of reaching a better situation.

This observation works symmetrically for minimum and maximum, which leads to some kind of ‚funnel' that restricts reasonable moves to lie in its interior; see Figure 4. A crucial point is how narrow this funnel can be made. For broad funnels, the heuristic will not discard a significant number of moves. If the funnel is too restrictive, on the other hand, we might skip strong moves and thus miss important positions. Choosing the optimum is, of course, strongly dependent on the specific game. For Abalone we determined the best value through careful experiments. Two observations were made when continuously changing the width of the funnel: while the improvement in runtime changed rather continuously, there was a critical threshold where the strength of play decreased dramatically. We considered the following criterion important in finding an optimal funnel width: playing on level $d+1$ with heuristic alpha-beta pruning switched on should always be superior to playing on level d with the heuristic switched off.

Performance and strength

Let us first take a look at the efficiency of our program. Table 1 compares the different approaches in two extremal situations: starting phase (new opening) and end game.

Strategy	Opening	Ending
Minimax strategy	60	65
Alpha-beta pruning	15	28
Presorted alpha-beta	13	13
Optimal alpha-beta	9	9
Heuristic alpha-beta	5	8

Table 1: Average number of moves per position

The table shows the average number of moves per position which had to be considered, i.e., the average branching factor B in the exponential complexity term before. We see that the employed strategies lead to significant improvements. In particular, our final alpha-beta heuristic cuts down B by a factor around 10 (!) compared to the simple minimax search. For the concrete example we gave earlier - where one move took over 5 years - this means that a move now can be found in about one second! (To be consistent with the PC times in Figure 5, we have to multiply these times by 50.) Figure 5 displays the runtime for different strategies and increasing depth levels, in the opening phase. The results for the ending phase are similar though less distinguishing between different strategies. As a satisfactory result, our heuristic clearly outperforms optimal alpha-beta pruning.

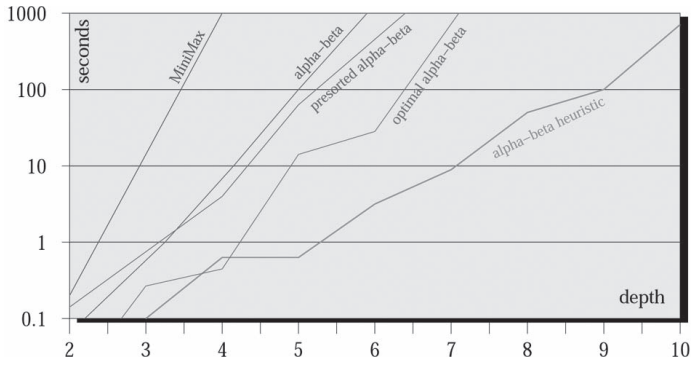


Fig.5: *Comparison of runtime for the different approaches*

To evaluate the strength of our program we could win Gerd Schnider, three times World Champion of Abalone, as a human opponent. During the different stages of implementation and development we had several pleasant surprises. For example, the program already ‚developed' its individual opening strategy. At first glance, Schnider was disappointed by this unconventional and ‚obviously weak' opening - but after a closer analysis he considered it as quite strong. Moreover, when playing against the program at level 7, he got into serious trouble and couldn't beat it, despite retrying several strategies. Finally he joked, „Maybe you should look for another test person." This convinced us that, although a lot of future work remains to be done, our current implementation[2] already plays quite well and offers a challenge for every fan of Abalone.

„I played against the program quite a few times and it is really strong. I was not able to beat it in lightning games (around 5 seconds per move), mostly because it defends weaker positions extremely well. Tactically it can look ahead further than me but there are still some shortcomings in its strategy - to my opinion it should pay more attention to the compactness of the marbles, and it under-estimates the importance of the center a little. Anyway, it is much stronger than all other programs I played against. With its help, Abalone theory will improve much faster than today."

Gert Schnider, three times World Champion of Abalone

■

2 A preliminary evaluation version of the program is available at http://www.igi.TUgraz.at/oaich/abalone.html

Dr. Oswin Aichholzer, computer scientist and mathematician, Ph.D. under Prof. Franz Aurenhammer, recipient of an APART-stipendium (Austrian Programme for Advanced Research and Technology) of the Österreichische Akademie der Wissenschaften.
Homepage: http://www.igi.tugraz.at/oaich

Prof. Dr. Franz Aurenhammer, computer scientist and mathematician, Ph.D. under Prof. H. Maurer at the TU Graz, Professor at the Institut für Grundlagen der Informationsverarbeitung der TU Graz, Head of the research group on algorithms and computational geometry.
Homepage: http://www.igi.tugraz.at/auren

Tino Werner, student of Telematik at the TU Graz, with focus on intelligent programs.

Voronoi Diagrams - Computational Geometry's Favorite

Oswin Aichholzer and Franz Aurenhammer*
Institut für Grundlagen der Informationsverarbeitung,
Technische Universität Graz

Introduction

Computational Geometry is the name of a young and dynamic branch of computer science. It is dedicated to the algorithmic study of elementary geometric questions, arising in numerous practically oriented areas like computer graphics, computer-aided design, pattern recognition, robotics, and operations research, to name a few. Computational geometry has attracted enormous research interest in the past two decades and is an established area nowadays. It is also one of the main research areas at our institute. The computational geometry group at IGI is well recognized in the international competition in that field.

„Imagine a large modern-style city which is equipped with a public transportation network like a subway or a bus system. Time is money and people intend to follow the quickest route from their homes to their desired destinations, using the network whenever appropriate. For some people several facilities of the same kind are equally attractive (think of post offices or hospitals), and their wish is to find out which facility is reachable first. There is also commercial interest (from real estate agents, or from a tourist office) to make visible the area which can be reached in, say one hour, from a given location in the city (the apartment for sale, or the recommended hotel). Neuralgic places lying within this 1-hour zone, like the main square, train stations, shopping centers, or tourist attraction sites should be displayed to the customer."

From: Quickest Paths, Straight Skeletons, and the City Voronoi Diagram [2].

The complexity (and appeal) hidden in this motivating every-day situation becomes apparent when noticing that quickest routes are inherently complex: once having accessed the transportation network, it may be too slow to simply follow it to an exit point close to the desired destination; taking intermediate shortcuts by foot walking may be advantageous at several places. Still, when interpreting travel duration as a kind of distance, a metric is obtained. *Distance problems*, as problems of this kind are called, constitute an important class in computational geometry.
In this context, there is one geometric structure which is maybe most famous in computational geometry: *Voronoi diagrams*. Intuitively speaking, a Voronoi diagram divides the available space among a number of given locations (called sites), according to the nearest-neighbor rule: each site *p* gets assigned the region (of the plane, say) which is closest to *p*. A honeycomb-like structure is obtained; see Figure 1.

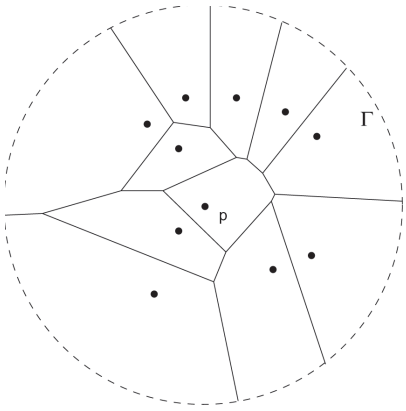


Fig.1: *Voronoi regions - aesthetically pleasing*

Christened after the Russian mathematician George Voronoi - believed to be the first to formally introduce it - this diagram has been reinvented and used in the past century in various different sciences. Area-specific names like Wigner-Seitz zones (chemics, physics), domains of action (cristallography), Thiessen polygons (geography), and Blum's transform (biology) document this remarkable fact. As of now, a good percentage of the computational geometry literature (about one out of 16 publications) is concerned with Voronoi diagrams. The computational geometry research group at Graz has been involved in this topic even before it became popular in the early 1980s (and long before our present institute has been founded). In this sense, research on Voronoi diagrams is a tradition at our place. For example, some 30 publications by the second author, including two survey articles [4] [6] (the former also available in Japanese translation [5]) have emerged from this preference.
We devote the present article to this fascinating geometric structure, with the intention to highlight its manifold role in computer science. Voronoi diagrams have proved to be a powerful tool in solving seemingly unrelated computational questions, and efficient and reasonably simple techniques have been developed for their computer construction and representation. Moreover, Voronoi diagrams have surprising mathematical properties and are related to many well-known geometric structures. Finally though, human intuition is guided by visual perception: if one sees an underlying structure, the whole situation may be understood at a higher level.

Classical applications

Voronoi diagrams capture the distance information inherent in a given configuration of sites in a compact manner. Basically, the structure is built from *edges* (portions of perpendicular bisectors between sites) and *vertices* (endpoints of edges). To represent a Voronoi diagram in a computer, any standard data structure for storing geometric graphs will do. Nonetheless, several tailor-made representations have been developed,

* Research supported by APART [Austrian Programme for Advanced Research and Technology of the Austrian Academy of Sciences]

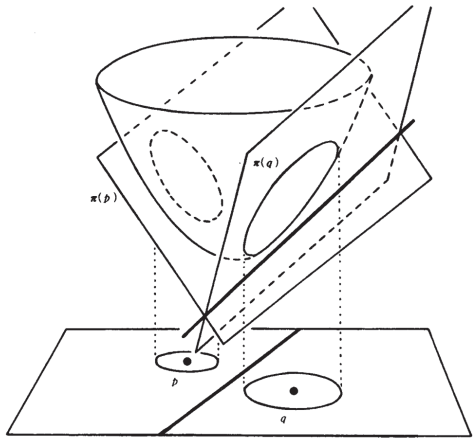


図 32 コーディルの空間における解釈 [Aurenhammer 1987a]

$$f_j=\sum_{i=0}^{a}\binom{i}{j}\binom{n-d+i-2}{i}+\sum_{i=0}^{b}\binom{d-i+1}{j}\binom{n-d+i-2}{i},$$

$$a=\lceil\frac{d}{2}\rceil,\quad b=\lfloor\frac{d}{2}\rfloor$$

である．これは，いわゆる上限定理 [Brondsted 1983] から得られる．$0\leq j\leq d-1$ に対する f_j の値は $O(n^{\lceil d/2\rceil})$ である．

パワー図の胞体は，凸多面体の面に対応しているから，凸であるが無限に延びた多面体となることもある．†22 すべての半空間が凸多面体の面として貢献するわけではないから，パワー図の胞体は空であったり1点に退化していたりすることもある．R^{d+1} における $(d+1)$ 個以上の超平面の交点が頂点となるから，パワー図における頂点には少なくとも $(d+1)$ 個の胞体が接続している．特に S の要素数が d を超えなければ，頂点は1個も生じない．PD(S) に関するこれらの性質およびその他の多くの性質を，$(d+1)$ 次元へのこのような埋込みの構造から容易に読み取ることができる．

3.1.2 超平面交差図形

状況をもっと完全に把握するために高階 Voronoi 図へ注意を向けることにする [Edelsbrunner 1987; Aurenhammer 1987a]．そのために，パワー胞体を母点が1個より多い場合へ拡張する．T を S の中の k 個の母点からなる集合としよう．T のパワー胞体は

$$\mathrm{cell}(T)=\bigcap_{p\in T,q\in S-T}h(p,q)$$

で定義される．k を固定したとき，S の $\binom{n}{k}$ 個の部分集合から上のように定義されるパワー胞体の（空ではないもの）全体がなす複体を，S の k 階パワー図 (order-k power diagram) と呼び，k-PD(S) で表わす．明らかに 1-PD(S)＝PD(S) である．S に属すすべての母点の重みが等しければ，k-PD(S) は単なる k 階 Voronoi 図となることに注意されたい．($n-1$)-PD(S) は最遠 (farthest site) パワー図とも呼ばれる．

さて，すべての $p\in T$ に対する超平面 $\pi(p)$ より下方の半空間と，すべての $q\in S-T$ に対する超平面 $\pi(q)$ の上方の半空間の共通部分を Z としよう．の

†22 (訳注) この文の最初の「多面体」は $d+1$ 次元，次の「多面体」は d 次元である．

Fig.2: *3D view of sites and distances*

the most popular one being the quad-edge data structure. Simple graph-theoretical arguments show that there are at most 3*n*-6 edges and 2*n*-4 vertices for *n* sites. In other words, the storage requirement is only *O*(*n*), which gives one more reason for the practical applicability of Voronoi diagrams.

Continuing from our introductory example, imagine the given sites are post offices. Then, for any chosen location of a customer, the containing Voronoi region makes explicit the post office closest to him/her. More abstractly, by performing point location in the data structure ‚Voronoi diagram', the nearest neighbor site of any query point can be retrieved quickly. (In fact, in *O*(log *n*) time. This is optimal by a matching information-theoretic bound). Similarly, sites may represent department stores, and Voronoi neighborhood - witnessed by diagram edges - will indicate stores in strongest mutual influence (or competition). Apart from economics, this basic finding has far-reaching applications in biological and physico-chemical systems. On the other hand, Voronoi vertices are places where the influence from sites reaches a local minimum - a fact of interest in facility location. Similar observations apply to the robotics scenery: sites are snapshots of moving robots, and danger of collision is most acute for the closest pair. Moreover, when planning a collision-free motion of a robot among a given set of obstacle sites, sticking to the boundaries of Voronoi regions (that is, moving along Voronoi edges and vertices) will keep the robot off the obstacles in a best possible way. (This is known as the retraction approach in motion planning.)

Numerous other applications of Voronoi diagrams exist, one notable being geometric clustering. The grouping of data sites into a cluster structure is reflected by their Voronoi regions. (For instance, dense clusters give rise to regions of small area.) Even more important is the fact that prominent types of optimal clusterings are induced by Voronoi diagrams, namely by partition with regions (which are not necessarily defined by the data sites to be clustered).

Two important and beautiful geometric structures cannot be hidden at this point. Firstly, any *shortest connection network* for the sites (think of a road or a electricity network) will solely connect sites which are Voronoi neighbors. Secondly, the graph connecting all the neighbored sites is a triangular network, called the *Delaunay triangulation*. Among all possible ways to build a triangular irregular network (TIN) the Delaunay triangulation is provably optimum, in several respects concerning the shape and size of its triangles (or tetrahedra, when it comes to higher dimensions). It is for this reason that Delaunay triangulations have been extensively used in surface generation, solid modeling, and related areas.

Beside shortest connection networks (or minimum spanning trees, as they are called in computational geometry) there are several other classes of geometric *neighborhood graphs* which are contained in the Delaunay triangulation: α-shapes (a tool in surface modeling), β-skeletons (with applications to the famous and still unsettled minimum-weight-triangulation problem), Gabriel graphs (geographic information systems (GIS)), and nearest-neighborhood graphs (pattern recognition).

Algorithms designer's playground

Methods for constructing Voronoi diagrams are as old as their use in the diverse areas of natural sciences. Of course, the first diagrams have been drawn with pencil and ruler. At these early times, people already complained about ambiguities if the sites come in a co-circular fashion. Nowadays, where sophisticated, efficient, and practical construction algorithms exist, robustness in the case of degenerate input sites is still an issue, and much of the program designers work goes into the implementation of ‚special cases'. The heart of an algorithm, however, is the underlying paradigmatic technique, and rarely a problem has been better a playground for algorithms design than the computation of a Voronoi diagram.

Beside other intuitive construction rules, *incremental insertion* has been among the first algorithmic techniques applied to Voronoi diagrams. This technique is well known from InsertionSort, a simple sorting method that maintains a sorted list during the insertion of items. In our case, insertion of a site means integrating its Voronoi region into the diagram constructed so far - a process that involves the construction of new and the deletion of old parts. Though the approach stands out by its simplicity and obvious correctness, the resulting runtime may be bad: finding a place to start the insertion is tricky, and many already constructed parts may have to be deleted lateron. It required the advent of *randomization* to give this approach an efficiency guarantee. To be more specific, inserting *n* sites in random order leads to an (expected) runtime of *O*(*n* log *n*) which is provably optimal. And only (almost-)optimal algorithms come up to a big advantage of the data structure Voronoi diagram: the linear storage requirement, *O*(*n*).

„The intrinsic potential of Voronoi diagrams lies in their structural properties, in the existence of efficient algorithms for their construction, and in their adaptability."

From: Handbook of Computational Geometry [5], Chapter V.

Though the ancient Romans definitely knew about the power of „divide et impera“, its algorithmic analog *divide & conquer* is often considered a less intuitive technique. It achieves efficiency by splitting the problem at hands, then solving the subproblems separately (and recursively), and finally merging the solutions. Voronoi diagrams are well suited to this attack. After presorting the sites (in x-direction, say) the merging of two subdiagrams can be done in $O(n)$ time, which calculates to a total runtime of $O(n \log n)$ by the recurrence relation $T(n) = 2 \cdot T(n/2) + O(n)$. Divide & conquer provided the first optimal algorithm for Voronoi diagrams, but certain peculiarities are buried in its implementation. On the other hand, it is a candidate for efficient parallelization.

Two more optimal construction techniques are known, both being specific to geometry. The *plane-sweep technique* sweeps the plane containing the n input sites with a vertical line L, from left to right, say. Thereby, it maintains the invariant that all parts of the object to be constructed, which lie to the left of L, have already been completed. In this way, a 2D static problem (the construction of a Voronoi diagram) is translated into a 1D dynamic problem (the handling of the interactions near the sweep line). When utilizing the advanced data structures ‚priority queue‘ and ‚dictionary‘, this event-driven algorithm runs in $O(\log n)$ time per event, the number of which is proportional to the size of a Voronoi diagram, $O(n)$.

Finally, *geometric transformation* is an elegant tool to gain algorithmic efficiency, via mapping a given problem to a better understood (and preferably solved) one. Its application to Voronoi diagrams is described in the next paragraph.

Back to geometry

Figure 2 gives a flavor of how proximity in 2D may be expressed by convexity in 3D. The surprising observation that a 2D Voronoi diagram is nothing but a projected convex 3D polyhedron opens our eyes - and a door to new construction methods. Polytope theory tells us to look for the geometric dual of that polyhedron (which now is the *convex hull* of n points in 3D), and indeed there is a simple rule to obtain these hull points directly from the given Voronoi sites: project them onto the paraboloid of rotation. The careful reader may notice that this very convex hull projects back to the afore-mentioned Delaunay triangulation of the sites in the plane. Convex hull algorithms are well established in computational geometry, and practical and robust implementations (running in time $O(n \log n)$ in 3D) are available.

Noteworthy more is hidden in the geometric relation mentioned above. Firstly, the theory of convex polytopes allows us to exactly analyze the number of individual components of a Voronoi diagram. This is a highly non-trivial task in three and higher dimensions; faces of various dimensions (vertices, edges, facets, etc.) have to be counted in a thorough analysis of the storage requirement. Secondly, a connection to *hyperplane arrangements* is drawn, that is of importance when Voronoi diagrams are modified to order k. Here subsets of k sites get assigned their Voronoi regions; they carry the information for efficiently performing k-nearest neighbor search.

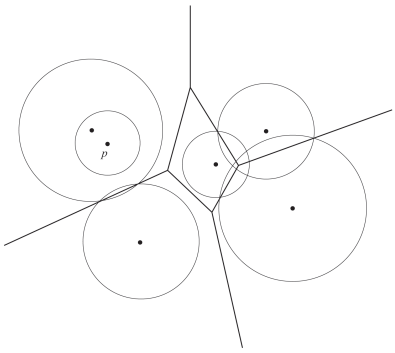


Fig.3: *Power diagram for 6 circles*

Finally, a natural generalization arises in the light of the geometric transformation shown in Figure 2. *Power diagrams*, defined by circular or spherical sites, and retaining the convexity of the regions. They constitute exactly those diagrams that are projected boundaries of convex polyhedra; Voronoi diagrams are special cases where circles degenerate to point sites. (When writing his doctoral thesis, the second author was excited when discovering the beauty and versatility of this structure; its name has been coined after one of his papers [3].) Power diagrams in 3D are related to important types of Voronoi diagrams in 2D, and thus provide a unified view of these structures. Among them are diagrams for sites with individual weights, expressing their capability to influence the neighborhood. These flexible models are used in other areas of science (Johnson-Mehl model in chemics and Appolonius model in economics). Even the mathematical physicist Clerk Maxwell in 1864 (implicitly) payed attention to power diagrams: he observed that a diagram reflects the equilibrium state of a spider web just if the diagram comes from projecting a polyhedron’s boundary...

A novel concept

In order to meet practical needs, Voronoi diagrams have been modified and generalized in many ways over the years. Concepts subject to change have been the shape of the sites (standard: points), the distance function used (standard: Euclidean metric), or even the underlying space (standard: the plane or 3-space). It is not appropriate here to give a systematic treatment of the various existing types of Voronoi diagrams. Instead, we would like to report on a particular type, which has been recently introduced and highlighted with success by our research group.

Let us aid the reader’s intuition by giving a physical interpretation of Voronoi diagrams. Imagine a handful of small pebbles being thrown into a quiet pond, and watch the circular waves expanding. The places where waves interfere are equidistant from the pebbles’ hitting points. That is, a Voronoi diagram is produced. (This is the so-called growth model in biology and chemics.)

Straight skeletons [1] are diagrams induced by wavefronts of more general shape. Consider a set, F, of simple polygons (called figures) in the plane. Each figure in F is associated with a birth time, and an individual speed for each of its edges to move in a self-parallel fashion. In this way, each figure sends out a polygonal wavefront (actually two, an external and an internal one). The straight skeleton of F now is the interference pattern of all these wavefronts, under the requirement that their expansion ceases at all points where wavefronts come into contact or self-contact.

During their propagation, the wavefront edges trace out planar and connected Voronoi diagram-like regions. Wavefront vertices move at (speed-weighted) angle bisectors for edges, and thus trace out straight line segments. We originally intended straight skeletons as a linearization of the *medial axis*, a widely used internal structure for polygons. (The medial axis is just the Voronoi diagram for the components of a polygon’s boundary. It contains parabolically curved edges if the polygon is non-convex.) In numerous applications, e.g., in pattern recognition, robotics, and GIS, skeletonal partitions of polygonal objects are sought that reflect shape in an

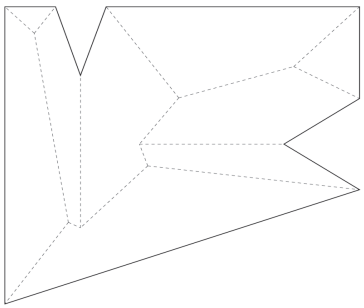


Fig.4: *Internal straight skeleton*

appropriate manner. The straight skeleton naturally suits these needs; see Figure 4. It is superior to the medial axis also because of its smaller size.

Curiously enough, straight skeletons do not admit a distance-from-site definition, in general (and therefore are no Voronoi diagrams in the strict sense). This counter-intuitive finding outrules the well-developed machinery for constructing Voronoi diagrams; merely a simulation of the wavefront expansion will work. The theoretically most efficient implementation runs in roughly $O(n\sqrt{n})$ time, and a triangulation-based method that maintains ‚free-space' exhibits an $O(n \log n)$ observed behavior for many inputs.

Straight skeletons apply to seemingly unrelated situations. This partially stems from a nice 3D interpretation, which visualizes the movement of each wavefront edge as a facet in 3D. The expansion speed of the edge determines the slope of the facet. In this way, each figure gives rise to a polyhedral cone in 3D, whose intersection with the plane is just the figure itself. The surface made up from these cones projects vertically to the straight skeleton. See Figure 5 for an illustration.

A problem from architectural design is constructing a roof that rises above a given outline of a building's groundwalls. This task is by no means trivial as roofs are highly ambigous objects. A more general question is the reconstruction of geographical terrains (say, from a given river map with additional information about elevation and slope of the terrain), which is a challenging problem in GIS. The straight skeleton offers a promising approach to both questions. Of particular elegance is the following property: the obtained 3D surfaces are characterized by the fact that every raindrop that hits the surface facet f runs off to the figure edge that defines f. This

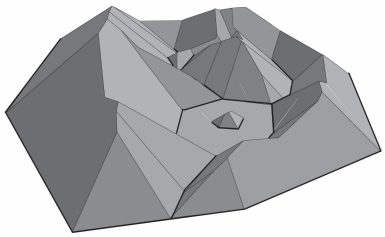


Fig.5: *Terrain reconstructed from river map*

applies to the study of rain water fall and the prediction of floodings.

Finally, there is an application to a classical question in origami design that deserves mention: is every simple polygon the silhouette of a flat origami? An affirmative answer has been found recently. The used method is based on covering certain polygonal rings that arise from shrinking the polygon in a straight skeleton manner. That is, our concept of straight skeleton allows for a relatively simple proof of this long-standing open conjecture in origami theory.

...and the city Voronoi diagram

Whereas the standard Voronoi diagram has interpretations in both the wavefront model and the distance-from-site model, this is not true for other types. Remember that straight skeletons cannot be defined in the latter model. Conversely, the occurance of disconnected Voronoi regions (as in the Apollonius model, where distances are weighted by multiplicative constants) disallows an interpretation in the former model. We conclude this article with a non-standard and demanding structure, that we have investigated recently, and that bridges the gap between both models.

The structure in question - we called it the *city Voronoi diagram* [2] - is just the diagram matching the motivating example in the introduction. Recall that we are given a city transportation network that influences proximity in the plane. We model this network as a planar straight-line graph C with horizontal or vertical edges. No other requirements are posed on C - it may contain cycles and even may be disconnected.

By assumption, we are free to enter C at any point. (This is not unrealistic for a bus system with densely arranged stops, and exactly meets the situation for shared taxis which regularly drive on predetermined routes and will stop for every customer.) Once having accessed C we travel at arbitrary but fixed speed $v > 1$ in one of the (at most four) available directions. Movement off the network takes place with unit speed, and with respect to the L_1(Manhattan) metric. (Again, this is realistic when walking in a modern city).

Let now $d_C(x, y)$ be the duration for the quickest route (which of course may use the network) between two given points x and y. When viewed as a distance function, this ‚city metric' d_C induces a Voronoi diagram as follows. Each site s in a given point set S gets assigned the region

$$reg(s) = \{x \mid d_C(x,s) < d_C(x,t), \forall t \in S \setminus \{s\}\}.$$

Setting equality in this term gives the bisector of two sites s and t. This is the locus of all points which can be reached from s and t within the same (minimum) time. Bisectors are polygonal lines which, however, show undesirable properties in view of an algorithmic construction of the city Voronoi diagram. By C's influence, they are of non-constant size, and even worse, they may be cyclic. These are main obstacles for efficiently applying divide & conquer and randomized incremental insertion.

The key for a proper geometric and algorithmic understanding of the city Voronoi diagram lies in the concept of straight skeletons. Let us ignore the network C for a moment. The L_1-metric Voronoi diagram for the sites in S already is a straight skeleton. Its figures are the L_1 unit circles (diamonds) centered at the sites. How does the network C influence their wavefronts? Their shapes change in a pre-determined manner, namely whenever a wavefront vertex runs into a network segment, or a wavefront edge slides into a network node. A new diamond will appear at such a place, along with tangent sharp-angled wedges whose peaks move at speed v in all possible directions on C. All these diamonds and wedges are taken as new figures. Together with the original L_1 diamonds, their straight skeleton now gives the city Voronoi diagram.

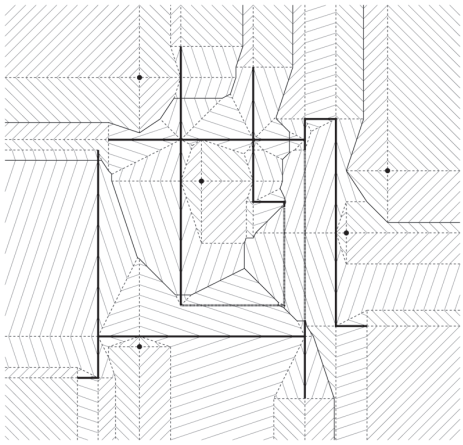


Fig.6: *A complex transportation network C (bold segments) and the city Voronoi diagram (full edges) for a set S of five sites scattered among C. The diagram is refined by straight skeleton edges (dashed). Quiet ranges occur in the network, shown as dotted subsegments. They could be closed down without delaying any quickest path to S. Also, one site is isolated from the network (the rightmost site s), in the sense that from nowhere in its region the quickest path to s takes advantage of C.*

In fact, the obtained skeleton contains a lot more edges (and information). Given a query point q, not only the first site s in S reachable from q can be retrieved, but rather the quickest route from q to s itself - a polygonal path of possibly high complexity. Still, this refined city Voronoi diagram has a size of only $O(n+c)$, where n and c denote the complexity of S and C, respectively. (This important property is lost for non-isothetic

networks or for the Euclidean metric; the size blows up to quadratic.)

Two major difficulties have to be mastered before arriving at an efficient construction algorithm. Firstly the set of figures, when constructed from S and C as sketched above, contains high redundancy for various reasons. Secondly, when having available the set of $O(n+c)$ non-redundant figures, a fast way of computing their straight skeleton has to be found. The second goal is achieved by modifying the figures so as to fit into the framework of so-called *abstract Voronoi diagrams*.

This general and elegant framework extracts the desired algorithmic properties of a Voronoi diagram. It is based on an admissible system of bisectors, rather than on some distance from the sites. For example, for each triple of abstract sites, any point common to two bisectors must also belong to the third. (This property is trivially fulfilled for any distance-defined diagram, but is violated by straight skeletons, in general. ‚No-man's lands' belonging to no figure would arise from this ill-conditioning.) In our case, a careful adaption of the figures does allows a reduction to abstract Voronoi diagrams. The refined city Voronoi diagram then can be constructed in $O(n \log n + c^2 \log c)$ time and optimal space.

Fig.7: *Direction-sensitive diagram [7]. Quo vadis?*

References

This choice of references is highly selective. In particular, we refrained from listing all our publications relevant to Voronoi diagrams; this is done elsewhere in the present issue.

[1] O.Aichholzer, F.Aurenhammer, Straight skeletons for general polygonal figures in the plane. In: Voronoi's Impact on Modern Sciences II, A.M.Samoilenko (ed.), Proc. Institute of Mathematics of the National Academy of Sciences of Ukraine 21, Kiev, Ukraine, 1998, 7-21.

[2] O.Aichholzer, F.Aurenhammer, B.Palop, Quickest paths, straight skeletons, and the city Voronoi diagram. Proc. 18th Ann. ACM Symp. Computational Geometry 2002.

[3] F.Aurenhammer, Power diagrams: properties, algorithms, and applications. SIAM Journal on Computing, 16 (1987), 78-96.

[4] F.Aurenhammer, Voronoi diagrams - a survey of a fundamental geometric data structure. ACM Computing Surveys 23 (1991), 345-405.

[5] F.Aurenhammer. Voronoi diagrams - a survey of a fundamental geometric data structure (Japanese translation). BIT - ACM Computing Surveys '91, Kyoritsu Shuppan Co., Ltd.(1993), 131-185.

[6] F.Aurenhammer, R.Klein, Voronoi diagrams. Handbook of Computational Geometry, Chapter 5, J.Sack, G.Urrutia (eds.), Elsevier Science Publishing, 2000, 201-290.

[7] O.Aichholzer, F.Aurenhammer, D.Z.Chen, D.T.Lee, E.Papadopoulou, Skew Voronoi diagrams. Int'l. Journal of Computational Geometry & Applications 9 (1999), 235-247. ■

Dr. Oswin Aichholzer, computer scientist and mathematician, Ph.D. under Prof. Franz Aurenhammer, recipient of an APART-stipendium (Austrian Programme for Advanced Research and Technology) of the Österreichische Akademie der Wissenschaften.
Homepage: http://www.igi.tugraz.at/oaich

Prof. Dr. Franz Aurenhammer, computer scientist and mathematician, Ph.D. under Prof. H. Maurer at the TU Graz, Professor at the Institut für Grundlagen der Informationsverarbeitung der TU Graz, Head of the research group on algorithms and computational geometry.
Homepage: http://www.igi.tugraz.at/auren

Points and Combinatorics

Oswin Aichholzer, Franz Aurenhammer, Hannes Krasser+*
Institut für Grundlagen der Informationsverarbeitung,
Technische Universität Graz

Which point sets exist, anyway?

This intuitive question sketches the topic of the article at hands. Its relevance is apparent: a configuration of n points is the underlying structure for countless problems in computational and combinatorial geometry.

A *point set* is a (finite) collection of points in the plane, which are usually given by their x and y coordinates. In fact, point sets are among the simplest geometric objects that lead to non-trivial questions - in a geometrical, combinatorial, and algorithmic sense. Not surprisingly, most basic data structures in computational geometry have first been developed for point sets, and have been later generalized to more general objects, like line segments, circles, polygons, etc. Examples include geometric search trees, convex hulls, Voronoi diagrams (an accompaning article is devoted to this versatile structure), and many others. During the past two years, a good share of effort of our research group went into the systematic investigation of point sets of small size. Let us report on this original and challenging topic at this place.

„There is a point in pointing out points, in order to order them by order type."
The Realizing Enumerators O.F.&H.

Of course, there exist infinitely many different sets of n points, for a given number n. However, quite a large class of problems is determined already by the *combinatorial* properties of an n-point set, rather than by its metric properties. To be more specific, look at all the $\binom{n}{2}$ straight-line segments spanned by a given n-point set, as in Figure 1. Which of these line segments cross each other, and which don't, turns out to be important: point sets with the same crossing properties give rise to equivalent geometric structures. This is valid for many popular structures, like spanning trees, triangulations, polygonalizations, so-called k-sets, and many more.

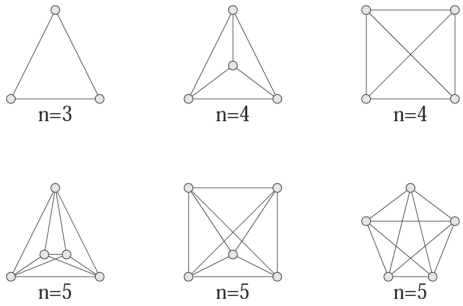


Fig.1: *Inequivalent sets of small size. There is only one (combinatorial) way to place 3 points, two ways to place 4 points, and three to place 5. The situation changes drastically for larger size.*

Several of these structures lead to notoriously hard problems. To gain insight, the study of typical (or extremal) instances is very fruitful. E.g., detecting a counter-example prevents us from constructing hopeless proofs. Conversely, the non-existence of counter-examples of small size gives some evidence for the truth of a conjecture. This motivates the complete enumeration of all problem instances of small size. In our case, this means investigating all *inequivalent* sets of points, where equivalence is with respect to their crossing properties. Let us ask again and more specifically, „Which inequivalent sets of, say 10, points do exist?"

The answer is surprisingly difficult, for two major reasons. Firstly, the number of inequivalent point sets of size 10 is already in the millions (14 309 547, to be precise). Secondly, there seems to be no simple way to enumerate all these sets. Each increase in set size gives rise to types which cannot be obtained directly from sets of smaller size. This may explain why it took until recently that an enumeration has been successful. We are proud to be the first having established (see [3]) and made available a complete and reliable data base[1] of all inequivalent 10-point sets (in December 2000). Meanwhile - in fact a few weeks ago - a further milestone was reached. We completed the generation of all inequivalent 11-point sets (in implicit form). The present article describes the inherent difficulties of such a project, along with numerous applications and results we obtained from our point set data base.

The theory behind

Order types

An appropriate tool to encode equivalence of point configurations has been developed by combinatorial geometers [15] quite a while ago. The *order type* of a set $\{p_1, ..., p_n\}$ of points is a mapping that assigns to each (ordered) index triple i, j, k the orientation - clockwise or counter-clockwise - of the point triple p_i, p_j, p_k. (We require that no three points lie on a common straight line.) Two point sets S_1 and S_2 are considered *equivalent* if they exhibit the same order types. That is, there is a one-to-one correspondence between S_1 and S_2 such that each triple in S_1 agrees in orientation with the corresponding triple in S_2. It is not hard to see that two line segments spanned by S_1 cross if

* Research supported by APART [Austrian Programme for Advanced Research and Technology of the Austrian Academy of Sciences] and the EU Improving Human Potential Programme HPRI-1999-CT-00071
+ Research supported by the FWF [Austrian Fonds zur Förderung der Wissenschaftlichen Forschung]

1 http://www.igi.TUGraz.at/oaich/triangulations/ordertypes.html

and only if their counterparts in S_2 do so. Our aim is to enumerate all order types of given size n, for $n \leq 11$.

Duality

We base our approach on a well-known *duality* between points and straight lines in the plane. By this duality, a set of points maps to a *line arrangement*, i.e., a dissection of the plane induced by a set of n straight lines. As no direct way to enumerate line arrangements is known, we first produce all (non-isomorphic) arrangements of so-called pseudolines. *Pseudolines* are simple curves that pairwise cross at exactly one point, just as non-parallel straight lines do. Handling pseudolines is relatively easy in view of their equivalent description by *wiring diagrams*; consult Figure 2. We can read off a corresponding *pseudo order type* from each wiring diagram: the order in which the wires cross each other determines the orientations for all index triples. Back in the primal setting, where each wire potentially corresponds to a point, this leads to a list of candidates guaranteed to contain all different order types.

Realizability

We are left with the problem of identifying all the *realizable* order types in the obtained list, that is, those for which corresponding point coordinates do exist. Here we enter the realm of *oriented matroids*, an axiomatic (combinatorial) abstraction of geometric objects, introduced in the late 1970s. As a known phenomenon, a wiring diagram need not be *stretchable* to straight. In fact, there exist non-stretchable diagrams already[2] for 8 wires [10]. As a consequence, our candidate list will contain *non-realizable* pseudo order types for size n ≥ 9. Moreover, even if realizability has been recognized for a particular candidate, how can we find a corresponding point set?

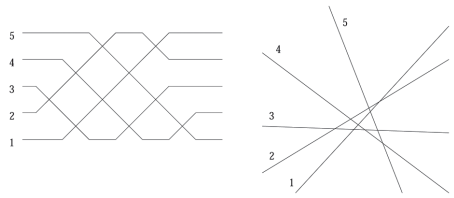


Fig.2: *A wiring diagram that can be stretched*

Projectivity

Surprisingly at first glance, the situation gets easier (conceptually and computationally) on the 3D sphere, that is, in the projective setting. To visualize projective order types, imagine all possible ways n stars can be arranged in the sky. Watching stars from a fast moving space vessel changes their geometry, but not their projective order type. Unlike before, order types now directly correspond to arrangements of great circles by duality (and isomorphism classes of pseudo-circle arrangements coincide with reorientation classes of rank 3 oriented matroids). Moreover, the desired order types in the plane can be nicely grouped into *projective classes*, and in every class either each or no order type is realizable.

Basic strategy

In a nutshell, our approach works as follows. It produces a candidate list of planar pseudo order types (from wiring diagrams), clusters them into projective classes, and tries to decide realizability for each class. A collection of all yet unrealized projective classes is maintained.

For problem sizes $n = 9$ and $n = 10$, the process could be terminated after the collection had shrunk to 1 and 242 members, respectively. We know from the literature that exactly that many classes are non-realizable [10, 14]. (The unique class for $n = 9$ derives from the well- known Pappus theorem.) For the case $n = 11$, however, where information about projective classes is completely lacking, a means for disproving realizability had to be applied.

Deciding realizability (for order types in particular and oriented matroids in general) is an intriguing problem, which is known to be NP-hard. Several heuristics have been developed; see [14] and references therein. For our case, a singly exponential algorithm exists but turned out to be too slow, already for problem size 10. Instead, we used a combination of methods with success. Even for size 11, we could decide upon the status of *all* the projective classes, i.e., distinguish the realizables from the non-realizables.

Coordinate recovering

We applied an obvious though powerful *insertion strategy* in a first step: obtain realizations of size n from realizations of size n-1. Suppose that, for each (realizable) order type T of size n-1, a corresponding point set $S(T)$ is available. Consider the arrangement $A(T)$ formed by $\binom{n-1}{2}$ lines, each passing through a pair of points in $S(T)$. Point sets of size n are now generated from $S(T)$, by placing an additional point in a cell of $A(T)$, for all possible cells. Carrying out this process for all existing order types of size n-1 leads to realizations for a majority of order types of size n.

However, the *geometry* of an (n-1)-point set $S(T)$ critically affects the set of order types of size n which actually get realized. (This principal difficulty makes order type enumeration a hard problem.) To increase effectiveness, we restarted the insertion method after random (but order type preserving) perturbations of the (n-1)-point sets. All but a vanishing fraction of the realizable order types could be detected in this way, in fact, over 99.99% even for $n = 11$. The rest (the ‚hard core' which contains the unrealizables, of course) we tried to realize directly - starting from scratch with tailor-made simulated annealing strategies.

n	3	4	5	6	7	8	9	10	11
Projective Pseudo Order Types	1	1	1	4	11	135	4 382	312 356	41 848 591
- thereof non realizable							1	242	155 214
= Projective Order Types	1	1	1	4	11	135	4 381	312 114	41 693 377
Planar Pseudo Order Types	1	2	3	16	135	3 315	158 830	14 320 182	2 343 203 071
- thereof non realizable							13	10 635	8 690 164
= Planar Order Types	1	2	3	16	135	3 315	158 817	14 309 547	2 334 512 907

Tab.1: Numbers of different order types of size n

Detecting non-realizability

Clearly, certain pseudo order types notoriously denied themselves to realization. An obvious method to disprove their realizability is by detecting some non-realizable sub-order type as a *witness*. Though being powerful like the insertion strategy before (as being its reverse), the method has similar drawbacks: not all cases are covered. We therefore had to unmask certain non-realizables by different means. Following [10], we utilized the so-called *Grassmann-Plücker* relations, a determinant relation fulfilled by each 5-tuple of points in the plane. For a given pseudo order type of size n, these $\binom{n}{5}$ relations lead to a linear program, whose infeasibility disproves its realizability.

2 Two of the authors won a pizza due to this peculiarity; the third was paying...

„...one notices a peculiar asymmetry between the realizable and the non-realizable cases. There exists a simple and systematic representation for realizability proof, namely a sample point configuration. Even the longest and most complicated derivation of a realizability proof can be discarded once we have found some coordinate matrix. This means that we only need a few real algebraic numbers to finally encode the proof."

From: Oriented matroids [10].

The data base

Output

Table 1 gives a quick overview of our results (in bold numbers), which significantly extend all relevant known results [14]. The tremendous growth of order types, especially in the planar case, becomes apparent. By the nature of our approach, we computed a combinatorial description for all the objects counted in Table 1, along with a geometric representation if the object is realizable. An obvious exception are the size-11 planar order types which - unless we are willing to spend some 160 CDs - have to be represented implicitly (by their projective classes).

Size 10

To get an impression of the computation time required, we give some details for the case n = 10. The generation of all pseudo order types, plus partial realization using insertion, took 36 hours on a 500 MHz Pentium III. Some 200 000 pseudo order types were left unrealized. Most of the corresponding projective classes got some member realized, however, and could be completed quickly by applying a projection technique. Only 251 projective classes of undecided status remained. For these, we had to invoke our simulated annealing routines, as we had no information on which are the 242 classes known to be non-realizable. We were successful for 9 classes within 60 hours which completed this task.

Size 11

As expected, the situation turned out to be much more complex for $n = 11$. Although we further improved the implementation, the total time spent on *projective classes* was more than three months on several processors. Their planar members (which we are mainly interested in) can be derived on-line and independently for each particular class, and thus need not be stored. We point out once more that the time-consuming routines (simulated annealing and Grassmann-Plücker) were used only in ‚emergency cases' where the insertion technique (and its reverse) were no help any more.

Whenever computing realizations, care was taken to avoid large coordinates. In addition, the simulated annealing routines were used to post-process the point sets. In their final form, our point sets enjoy several user-friendly properties, including a 16 bit integer representation. This should be contrasted with known negative results on the efficient grid embeddability of order types [16].

Reliability

Despite the theoretical correctness of the algorithms used, the question arises of how reliable are our implementations. The wiring diagram based calculation of planar pseudo order types, including their grouping into projective classes, is of purely combinatorial nature. Evidence of correctness is gained from the correctly computed total numbers of projective pseudo order types for $n \leq 10$ (which have been known before; see Table 1).

The critical part are the geometric routines for both, proving and disproving realizability. As realizabilty is witnessed by the point sets (in nice representation), it can be re-checked in a reliable way. Non-realizability, on the other hand, may have no direct witness. We therefore put particular emphasis on the clean implementation of the geometric part of the Grassmann- Plücker routine, which basically is a linear program.

Applicability

In summary, a data base has been obtained that is complete, user-friendly, and reliable. Small integer coordinates ensure that all calculations based on our data base are efficient and numerically stable. Due to storage limitations, the point sets for sizes 10 and 11 are not accessible on-line, but rather have been stored on CDs which are available from us upon request. We believe our data base to be of value to many researchers who wish to examine their conjectures on small point configurations.

The applicability of the data base is broad. In principle, any geometric straight-line structure is a candidate. Let us describe - for a few prominent questions - the progress achieved when using our data base. A more complete collection of our results is [5]. The concepts skipped here for space limitations include convex polygon covering, convex decomposition, pseudo-triangulations, *k*-sets (partitioning lines), as well as the crossing-free variants of polygonalizations (Hamiltonian cycles), spanning trees, and matchings.

Crossing numbers

The (rectilinear) *crossing number* of a graph G is the least number of edge crossings attained by a straight-line drawing of G in the plane. To avoid trivialities, no three vertices of G may be collinear in the drawing.

„...Our work was to bring out bricks from the ovens where they were made ...each oven was connected by rail with each store....trouble arose at the crossing of two rails. Here the cars jumped out, the bricks fell down; a lot of extra work and loss of time arose. Having this experience a number of times it occured to me why on earth did they build the rail system so uneconomically; minimizing the number of crossings the production could be made much more economical."

From [18], Turan's brick factory problem

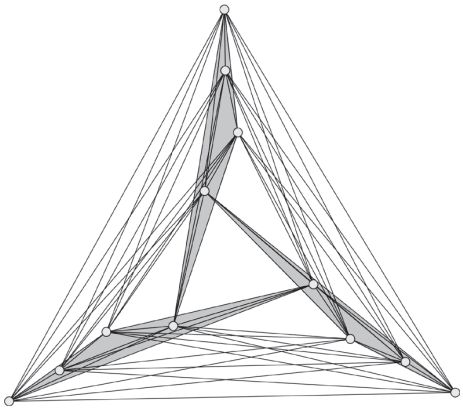


Fig.3: *Minimal drawing of* K_{12}

It is easy to prove that drawings which differ in their numbers of crossings stem from vertex sets of different order types. Our interest is in $\overline{cr}(K_n)$, the rectilinear crossing number of the *complete graph* K_n on n vertices.

Determining $\overline{cr}(K_n)$ is commonly agreed to be a difficult task. From an algorithmic point of view, deciding whether $\overline{cr}(G) \leq k$ for a given graph G and parameter k, is NP-hard [9]. Despite the remarkable hunt for crossing numbers - initiated in [17] in the 1960s - only for very small n the exact values of $\overline{cr}(K_n)$ have been known, until recently. The instances $n \leq 9$ have been settled quite a time ago, but no progress has been made until in 2001 two groups of researchers ([11] and the authors [3], respectively) independently found $\overline{cr}(K_{10}) = 62$. In [11] the goal was reached by a purely combinatorial argument, while our result came as a byproduct of the exhaustive enumeration of all order types of size 10.

Encouraged by this achievement, we tailored our approach to generate inequivalent drawings of

K_n for larger n. The effect was surprising. Not only could we completely resolve the situation for $n = 11$ (to be precise, $\overline{cr}(K_{11})$ is 102, and this value is attained by exactly 374 inequivalent drawings), we also could break new ground for $n = 12$. More specifically, $\overline{cr}(K_{12})$ is 153, and the only known drawing that attains this value is Figure 3. These findings also implied the best known lower bound on the limit

$$\lim_{n\to\infty} \overline{cr}(K_n) / \binom{n}{4} > 0.311507$$

which describes the ‚asymptotic gain' when drawing K_n optimally. In fact, this is a geometric quantity of separate interest, by a connection to Sylvester's four point problem [21]. For n ≥ 13, we constructed various new drawings of K_n with few crossings, by insertion into the small optimal examples. These drawings led to improved upper bounds for the quantity above. The tantalizing question of determining $\overline{cr}(K_{13})$ is left open. By our calculations, the latest ra(n)ge is {221, 223, 225, 227, 229}; our conjecture is $\overline{cr}(K_{13}) = 229$.

Compatible triangulations

Can any two planar point sets (within the obvious size and convex hull restrictions) be triangulated in the same manner? Surprisingly, this basic question - which has applications in computer graphics (morphing) and in cartography (PLH maps) - is still unsettled. A *triangulation* of a set S of points is a maximal collection of non-crossing edges (line segments) spanned by S. Two point sets of the same order type allow for the same variety of triangulations.

Triangulations are flexible constructs, which play a role in various areas and have important applications [8]; an obvious one is mesh generation. Their appealing structural properties won our interest right away. Beside Voronoi diagrams, triangulations have been the favorite structures of our research group; 15 publications arose in the last few years. Our work on this topic is partially reported in the survey article on optimal triangulations [7].

Returning to the question above, let S_1 and S_2 be two point sets in the plane. Two triangulations T_1 of S_1 and T_2 of S_2 are called *compatible* if there is a one-to-one correspondence φ: $S_1 \to S_2$ with the following property: for each empty triangle ijk in T_1, the points $\varphi(i)\varphi(j)\varphi(k)$ define an empty triangle in T_2; see Figure 4. Compatible triangulations show isomorphic graphs of edges; the converse is not true, in general.

The problem of triangulating two given point sets compatibly comes in two flavors, namely where the correspondence between their points is either fixed in advance, or variable. The case of *fixed correspondence* is a known problem. In particular, compatible triangulations do not always exist [19], because edges can be forced to cross (which is prohibited in a triangulation). The related decision problem is neither known to be NP-complete nor to be polynomially solvable. However, the problem becomes easier if the two point sets represent the vertices of two simple n-gons [6], namely decidable in $O(n^2)$ time. We asked the different question, „under which conditions does there exist a correspondence which allows for compatible triangulations?" Clearly, in both sets S_1 and S_2 the number n of points must be the same; as has to be the number h of *extreme* points (points on their convex hulls), by the well-known Eulerian formula $e = 3n-h-3$ for the number of triangulation edges.

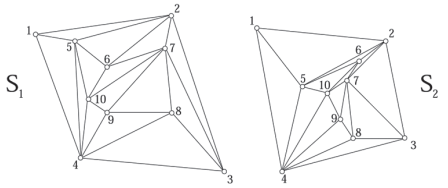


Fig.4: *These two triangulations are compatible*

Extreme points necessarily map to extreme points, and their cyclic order on the convex hulls is preserved. (More generally, for compatible triangulations any two corresponding triangles ijk and $\varphi(i)\varphi(j)\varphi(k)$ must match in orientation. That is, their point sets locally exhibit the same order type.) Finally, both point sets have to be in *general position*, i.e., no three points on the same line are allowed. Counter-examples exist, otherwise; see Figure 5.

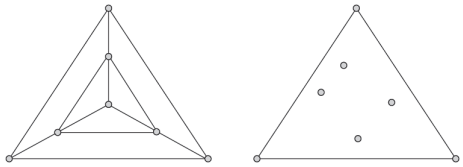


Fig.5: *No compatible triangulations exist*

These observations led us to state the following conjectures (which have been included in the recently founded open problems list in computational geometry[3]).

Main Conjecture

Any two n-point sets that agree in the number of extreme points, and both are in general position, admit a compatible triangulation.

Extended Conjecture

The Main Conjecture still holds if a correspondence between the extreme points is prescibed (by a cyclically shifted labeling).

The extended conjecture is relevant for a possible induction proof, which naturally will lead to assuming the stronger version as a hypothesis.

In [2] we undertook first steps towards proving the conjectures. For instance, they are true if the number of interior points in either set is three or less. Obtaining an affirmative answer would be a deep theoretical result, showing that all planar point sets of the same size and hull size are ‚topologically equivalent' in this very sense. The result, if true, gains in importance in view of the huge number of different order types for n points; cf. Table 1.

In order to encourage and support future research on this topic, we are glad to announce the reward below. (A related playing tool[4] may turn out helpful.)

ATTENTION - EuroPrizes!

- **30** for proving the Conjectures
  + an original Austrian Wiener Schnitzel
- **7** for a counter-example to the Main
- **5** for a counter-example to the Extended

No reward for proving the Conjectures and providing a counter-example at the same time!

Using our data base, we tested the Extended Conjecture for small point set sizes, and could verify it for up to 8 points. The lack of good heuristics for checking compatibility made the calculations time-consuming, however; they are still incomplete for size 9. Determining the theoretical complexity of computing compatible triangulations, if they exist, is an open problem. On the other hand, adding a small number of extraneous points (so-called Steiner points), which can be found efficiently, will always do the job [2].

Triangulation counting

Efficiently counting all possible triangulations of a given n-point set (in general position) is an interesting open problem. To give a motivation, the question relates to computing random triangulations - a concept of importance for testing triangulation-based algorithms.

The fastest counting method to date is based on a concept we called triangulation path [1]. Its running time still shows exponential growth,

3 http://www.cs.smith.edu/~orourke/TOPP/node39.html#Problem.38

4 http://www.igi.TUgraz.at/oaich/triangulations/compatible.html

however, and computations are limited to $n \le 40$. On the other hand, no good theoretical bounds on the number of triangulations are known. The current best maximizing examples yield $8^{n-\Theta(\log n)}$ triangulations, whereas the strongest upper bound is much larger, $59^{n-\Theta(\log n)}$; see [20].

Not even for small values of n, *exact numbers* have been known. But point sets of the same order type admit equally many triangulations, and so we could compute these numbers for $n \le 10$. Table 2 lists their extremum values. The currently best examples for n = 11 through 20 can be found on-line[5] .

n	minimum	maximum
3	1	1
4	1	2
5	2	5
6	4	14
7	11	42
8	30	150
9	89	780
10	250	4550

Tab.2: *Extremum numbers of triangulations*

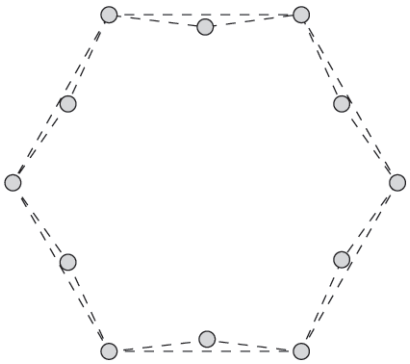


Fig.6: *Double-circle configuration*

So, for example, every set of 8 points must have at least 30 triangulations, and there actually exists a set having that few triangulations. This shows that point sets in convex position, whose number of triangulations is given by the so-called Catalan numbers $C(n\text{-}2)$ (yielding 132 for n = 8), do not lead to the minimum. This conjecture would have been plausible, as it is true for other structures, namely for crossing-free matchings and crossing-free spanning trees [13]. Though the conjecture has been resolved before, the results in Table 2 may be useful in proving or disproving the extremal behavior of other point configurations. For instance, we could observe that the point sets leading to the lower bounds in Table 2 obey a rather special structure. We conjecture that these ‚double-circle' configurations - shown in Figure 6 - indeed yield the minimum for general n.

A legitimate question is, „How many triangulations must every n-point set have?" Surprisingly little is known in this respect. We therefore seek for functions $t(n)$ such that every set of n points exhibits $\Omega(t(n))$ triangulations. A quick answer is $t(n) = 2^{(n-4)/6}$, because every triangulation on n points contains at least $(n\text{-}4)/6$ edges that can be flipped (i.e., replaced by a crossing edge within the same quadrilateral) in an independent way [12]. A substantial improvement is based, among other things, on a new result on *crossing families* (pairwise crossing edges), which we found out by checking order types: every set of 10 points already spans a crossing family of size 3. (This drastically improves on the previous best bound of 37, in [22].)

We exploited this result [4] to obtain the relation

$$t(n) \ge 3 \cdot t(n_1) \cdot t(n_2)$$

for $n_1+n_2 = n+2$. For any base α, the function $t(n) = 1/3 \cdot \alpha^{n-2}$ is a solution. To get the recurrence started, values of α as large as possible are sought by examining all instances of small constant size. This is done by utilizing Table 2, in combination with other methods. The best value we achieved is $\alpha = 2+\varepsilon$ for $\varepsilon < 1/80$, that is,

$$t(n) > \frac{1}{13} \cdot (2+\varepsilon)^n .$$

This constitutes the first bound that asymptotically beats the magic threshold 2^n.

The enumeration of combinatorial objects clearly is limited to small object size. Still, proving a general property may boil down to a case analysis of constant-size problems. Proofs that require a non-trivial induction base are an example . . . The point is that the quality of the induction base affects the asymptotics of the result. In this way, ‚constant' knowledge may well lead to insight concerning ‚infinity and beyond'...

References

[1] O.Aichholzer, The path of a triangulation. Proc. 15th Ann. ACM Symp. on Computational Geometry, 1999, 14-23.

[2] O.Aichholzer, F.Aurenhammer, F.Hurtado, H.Krasser, Towards compatible triangulations. Theoretical Computer Science (invited).

[3] O.Aichholzer, F.Aurenhammer, H.Krasser, Enumerating order types for small point sets with applications. Proc. 17th Ann. ACM Symp. on Computational Geometry, 2001, 11-18.

[4] O.Aichholzer, F.Hurtado, M.Noy, On the number of triangulations every planar point set must have. Proc. 13th Ann. Canadian Conf. on Computational Geometry, 2001, 13-16.

[5] O.Aichholzer, H.Krasser, The point set order type data base: a collection of applications and results. Proc. 13th Ann. Canadian Conf. on Computational Geometry, 2001,17-20.

[6] B.Aronov, R.Seidel, D.Souvaine, On compatible triangulations of simple polygons. Computational Geometry: Theory and Applications 3 (1993), 27-35.

[7] F.Aurenhammer, Y.-F.Xu, Optimal triangulations. In: Encyclopedia of Optimization 4, P.M.Pardalos and C.A.Floudas (eds), Kluwer Academic Publishing, 2001, 160-166.

[8] M.Bern, D.Eppstein, Mesh generation and optimal triangulation. In: D.-Z.Du, F.K.Hwang (eds.), Computing in Euclidean Geometry, Lecture Notes Series in Computing 4, World Scientific, Singapore, 1995, 47-123.

[9] D.Bienstock, Some provably hard crossing number problems. Discrete & Computational Geometry 6 (1991), 443-459.

[10] A.Björner, M.Las Vergnas, B.Sturmfels, N.White, G.Ziegler, Oriented Matroids. Cambridge University Press, 1993.

[11] A.Brodsky, S.Durocher, E.Gether, The rectilinear crossing number of K_{10} is 62. The Electronic J. of Combinatorics 8 (2001), Research Paper 23.

[12] J.Galtier, F.Hurtado, M.Noy, S.Perennes, J.Urrutia, Simultaneous edge flipping in triangulations. Manuscript, Universitat Politecnica de Catalunya, Barcelona, Spain, 2000.

[13] A.García, M.Noy, J.Tejel, Lower bounds on the number of crossing free subgraphs of K_n, Computational Geometry: Theory and Applications 16 (2000), 211-221.

[14] J.E.Goodman, Pseudoline arrangements. In J.E.Goodman, J.O'Rourke (eds.), Handbook of Discrete and Computational Geometry. CRC Press LLC, Boca Raton, NY, 1997.

[15] J.E.Goodman, R.Pollack, Multidimensional sorting. SIAM J. Computing 12 (1983), 484-507.

[16] J.E.Goodman, R.Pollack, B.Sturmfels, Coordinate representation of order types requires exponential storage. Proc. 21st Ann. ACM Sympos. Theory of Computing, 1989, 405-410.

5 http://www.igi.tugraz.at/oaich/triangulations/counting/counting.html

[17] R.K.Guy, A combinatorial problem. Nabla (Bulletin of the Malayan Mathematical Society) 7 (1960), 68-72.

[18] R.K.Guy, The decline and fall of Zarankiewicz's theorem. In: Proof Techniques in Graph Theory (Proc. 2nd Ann Arbor Graph Theory Conf.), 63-69, Academic Press, New York, 1969.

[19] A.Saalfeld, Joint triangulations and triangulation maps. Proc. 3rd Ann. ACM Sympos. Computational Geometry, 1987, 195-204.

[20] F.Santos, R.Seidel, On the number of triangulations. Manuscript, Universität des Saarlandes, Saarbrücken, Germany, 2000.

[21] E.R.Scheinerman, H.S.Wilf, The rectilinear crossing number of a complete graph and Sylvester's „four point problem" of geometric probability. Amer. Math. Monthly 101 (1994), 939-943.

[22] G.Tóth, P.Valtr, Note on Erdös-Szekeres theorem. Discrete & Computational Geometry 19 (1998), 457-459. ■

Dr. Oswin Aichholzer, computer scientist and mathematician, Ph.D. under Prof. Franz Aurenhammer, recipient of an APART-stipendium (Austrian Programme for Advanced Research and Technology) of the Österreichische Akademie der Wissenschaften.
Homepage: http://www.igi.tugraz.at/oaich

Prof. Dr. Franz Aurenhammer, computer scientist and mathematician, Ph.D. under Prof. H. Maurer at the TU Graz, Professor at the Institut für Grundlagen der Informationsverarbeitung der TU Graz, Head of the research group on algorithms and computational geometry.
Homepage: http://www.igi.tugraz.at/auren

Dipl. Ing. Hannes Krasser, computer scientist and mathematician, Ph.D. student of Prof. Franz Aurenhammer at the Institut für Grundlagen der Informationsverarbeitung.
Homepage: http://www.igi.tugraz.at/hkrasser

Sorting it out: Machine Learning and Fingerprints

Anton Schwaighofer
Siemens Corporate Technology, München, and Institut für Grundlagen der Informationsverarbeitung, Technische Universität Graz

Abstract
Machine learning concepts can find applications in many domains. We describe here one such application to the problem of fingerprint verification. In biometric verification using fingerprints, one often has to handle large archives of fingerprint images. When verifying an individual fingerprint, it is important to have a fast method at hand that selects suitable candidate images out of a large archive. We present an approach to sort a fingerprint archive according to similarity with a given fingerprint, inspired by an opto-electronic device called the wedge-ring-detector.

The goal

With the advent of electronic banking, electronic commerce and smart-cards, more and more personal data - such as credit card numbers or medical records - is stored electronically. Reliable systems for automatic personal identification are becoming increasingly important. Fingerprints have become popular as a means of personal identification, since relatively cheap sensors are available. State-of-the-art fingerprint sensors occupy an area of a postage stamp and are less than 1 mm thick.

The framework for the work presented here is the Siemens ID Mouse, a computer mouse with an integrated fingerprint sensor. The main application area of the ID Mouse is access control to a PC. The user no longer has to enter his or her password to gain access, but simply puts a finger onto the fingerprint sensor.

When using the ID Mouse in large scale applications such as network-wide identification, methods to efficiently handle large archives of fingerprints become necessary. Using concepts developed in machine learning, we first devise a compact representation of fingerprint images, based on spectral features of the images. In a second step, a similarity function based on the chosen representation is tailored specifically to comparing fingerprint images. In combination, this gives an efficient and accurate method of sorting a large archive of fingerprints according to coarse level similarity with a given request fingerprint.

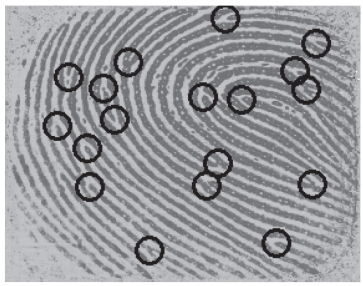


Fig.1: *An example fingerprint image. Classical fingerprint verification is based on the so-called minutiae, the end points and bifurcations of the finger ridges (marked by circles). When a sufficient number of minutiae in two fingerprints agree in both type and orientation, the fingerprints are assumed to be identical.*

Classical fingerprint recognition

Fingerprints are among the earliest and best-known biometric identification methods. Developed primarily for the identification of criminals, the use of fingerprints has been extended to, for example, amnesia victims or unknown deceased. Basis of classical fingerprint recognition techniques are the end points and bifurcations of the finger ridges, the so-called minutiae. A sample fingerprint image with marked minutiae is shown in Figure 1.

Fingerprint recognition systems based on minutiae consist loosely speaking of three stages: Image pre-processing, locating the minutiae, and comparing the minutiae list of both fingerprints, often solved as a constrained graph matching problem. Easy as this may sound at the first glance, this process has many stumbling blocks. Each of the processing steps requires careful fine-tuning of parameters and handling of ambiguous cases. Thus, the whole process of comparing two fingerprints may become rather time-consuming.

Spectral features of fingerprints

For our purposes, we wish to have a representation of fingerprint images that captures global image properties. Using such global features, fingerprints can be compared at a coarse global level first, and only at a second stage the local features (minutiae) will be used.

Due to the inherent periodic structure of a fingerprint, ridge frequency and ridge orientation seem to be a good choice. It is well known that the Fourier transformation of an image can

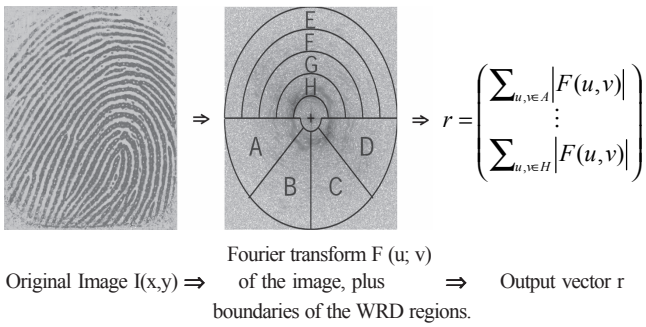


Fig.2: *The wedge-ring-detector (WRD) is applied to an image. The detector has 4 wedge-shaped regions A...D and 4 ring-shaped regions E...H. Integrating (resp. summing) the spectral energy of each region gives a feature vector r that is used as the representation for the fingerprint image I(x; y). This drawing is schematic, the wedge-ring-detector that is effectively being used has 12 rings and 8 wedges.*

capture such global features. When browsing through the literature, we came across a device inspired from opto-electronics, called the wedge-ring-detector (WRD). The idea of the WRD is as follows:

1. Compute the discrete Fourier transform of the image.
2. Partition the Fourier transform into wedge-shaped and ring-shaped regions. These regions correspond to different ranges and orientations of spatial frequency.
3. Integrating the Fourier transform over each of these regions gives a figure describing the amount of spectral energy in the corresponding region.

The whole process of applying the WRD to a fingerprint image is summarized in Figure 2. By checking the properties of the Fourier transform, we recognize that the features from integrating over rings are (to a certain extent) invariant under rotation. All features are (again only to a certain extent) invariant under translation, since the WRD integrates over absolute values. The wedge-ring- detector thus provides us with a single vector describing global and invariant properties of the fingerprint image.

Feature optimization

Above we have described the process of computing a global description of a fingerprint image by means of the so-called wedge-ring-detector (WRD). This method has been used for long in opto-electronics and also in some previous work on finger-print recognition [3].

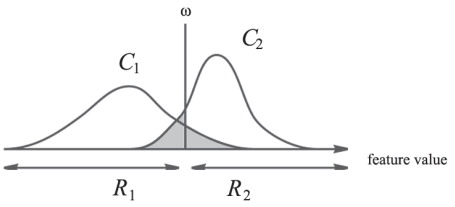


Fig.3: *The principle behind the Bhattacharrya bound. The plot shows the distribution of feature values for points from classes C1 and C2 . For both classes, the feature value has Gaussian distribution. We might now try to assign points to the classes C1 and C2 by setting a simple threshold ω. But since the two classes have a region of overlap, this classification will not be error free - no matter how sophisticated the classification scheme is. The error is proportional to the area marked gray in the plot. The Bhattacharrya bound gives a lower bound on the error, computed from mean and variance of the class distributions.*

At this point, machine learning (ML) finally comes into play. We use ideas from ML to improve on two distinct points:

1. We use a statistical criterion to optimize the position and size of wedges and rings, that is, the parameters of the WRD. It turns out that we can gain a lot of discriminative power by tailoring the WRD specifically to fingerprint images.
2. In a simple system, we might want to compare two fingerprint images only on the basis of their WRD feature vectors, leaving aside any other information such as minutiae. Using adaptive techniques, namely neural networks and support vector machines, we can learn a function that takes two WRD feature vector as input and computes the degree of similarity of the two corresponding fingerprint images.

To optimize the arrangement of wedges and rings in the WRD, we employ the so-called Bhattacharrya-bound [1]. Figure 3 briefly illustrates this concept. The basic idea of our optimization procedure is to look at pairs of fingerprint images, each fingerprint being represented by its WRD feature vector. Each pair either shows the same finger (call that class C_1) or two different fingers (class C_2). We assume that both classes have a Gaussian distribution. These two classes will not be separable perfectly, due to ambiguities in the images and mostly due to the simple representation via the WRD feature vector. This means that no method, no matter how sophisticated it is, can tell precisely whether the two fingerprint images show the same finger or not. The error of a (hypothetical) optimal method is bounded from below by the Bhattacharrya distance of the classes C_1 and C_2.

Our idea to find the optimal arrangement of rings and wedges in the WRD (the WRD parameters) is to minimize the Bhattacharrya distance. We choose the parameters such that the fingerprint representation allows a classification with minimum error. We proceed as follows: We iteratively modify one parameter, keeping all others fixed. With the current parameter setting, all feature vectors for a given set of fingerprint images are computed. We set the parameter to that value which minimizes the Bhattacharrya distance. We so found optimized values for the following parameters of the WRD:

- radius of the innermost and outermost ring
- inner and outer radius of the wedges
- number of rings and number of wedges

In existing literature, the WRD is always used in a non-optimized way. On a test set of 407 fingerprint images, the use of an optimized WRD with 20 rings and wedges lead to a reduction of error rates by 20%, when compared to the same setting with a non-optimized WRD (Table 2 lists the detailed results). Even higher improvements through the use of the optimized WRD will be shown in the last section.

An adaptive similarity function

In the previous section we have shown a method of representing a fingerprint image by a lowdimensional vector, computed with the wedge-ring-detector. Based on this representation we can now answer the question which fingerprint image in an archive (reference fingerprints) matches a given request fingerprint. We might do so by computing the Euclidean distance between feature vectors and select that reference fingerprint that has the lowest Euclidean distance. Such a simplistic approach will of course not be sufficiently accurate for practical use, yet it will become a very helpful tool in the next section.

It turned out that this simple strategy can be improved by means of an adaptive similarity function that replaces the Euclidean distance. We obtain the similarity function by using a learning algorithm. A learning algorithm as we use it here can be looked upon as a family of parameterized functions. Training points consist of function input value and desired output value. During training, the parameters of the learning algorithm are chosen to minimize an error criterion, evaluated on the training points. Output of the training stage is a function with optimally chosen parameters.

The training data for our task here are generated from a set of fingerprint images from 43 fingers, with 4 different images per finger. We consider each pair of fingerprint images, both represented by their wedge-ring-detector feature vector. If both images show the same finger, we set the corresponding target value to 1, otherwise to 0. It turned out that the best learning algorithm for this kind of problem was the Support Vector Machine (SVM, see for example [2]), a linear classifier that has been used with great success for problems ranging from handwritten digit recognition to text classification. Input to the SVM are two feature vectors representing fingerprint images, the SVM outputs the degree of similarity between the two images. Table 1 shows that the use of the SVM can improve the error rates of the above mentioned simplistic fingerprint recognition system by another 10%.

Overall system performance

Comparing two fingerprint images in detail is a very time-consuming task. When using a minutiae based approach (see Fig.1) the comparison boils down to comparing two minutiae lists. Minutiae in both images should agree in type (bifurcation or end point), orientation and distance to other minutiae. Since we have to account for rotation, translation, missing and false minutiae as well, this may become a lengthy procedure. This is not so much a problem as long as the number of reference fingerprints is small (say, 10). Once the number reaches 100 or even millions in large fingerprint databases, a simple matching strategy such as comparing the request fingerprint with all reference fingerprints is clearly unpractical.

Method	Error rate on test set
Non-optimized wedge-ring-detector, compare feature vectors via Euclidean distance (as used in literature)	14,7 %
Optimized wedge-ring-detector, compare via Euclidean distance	13,04 %
Optimized wedge-ring-detector,compare via Support Vector Machine	11,68 %

Tab.1: *Performance of a simplistic fingerprint recognition system. One can observe the reduction of error rates that is achieved by first optimizing the WRD specifically for fingerprint images, and secondly by using an adaptive function (SVM) to compare the feature vectors. The error rates are of course far too high to be used in a stand-alone system, yet they provide a good basis for use as a pre-matching system (see text)*

The whole process of fingerprint matching is thus being split up into two parts:

1. The *pre-matcher* selects those images from the archive of reference images that are most similar to the given request fingerprint. These images are called the candidate images. A suitable measure of similarity has to be defined.
2. The *matcher* takes the list of candidate fingerprints and performs a detailed comparison of the request fingerprint with all candidate fingerprints. If no matching fingerprint can be found in the candidate set, we assume that the request fingerprint does not match any of the reference images.

Based on the ideas presented in the previous sections, we propose the following pre-matcher. We first compute the wedge-ring-detector feature vector for the request image. Then scan over the whole archive of reference fingerprints and feed the WRD feature vectors of each reference fingerprint and request fingerprint into the adaptive similarity function. The pre-matcher selects now as the candidate set those reference images that show the highest degree of similarity to the request image. Since the reference feature vectors can be computed in advance, the pre-matcher can be run at low computational cost.
The identification system in the ID Mouse software has already been equipped with a prematcher, yet based on a different idea. We now compare the performance of our proposed pre-matcher to the performance of the currently used pre-matcher, using the following criteria:

- Overall error rate of the system (pre-matcher and matcher).
- Average position of the matching fingerprint in the candidate set (winner average position WAP). An ideal pre-matcher would place the one reference image that matches the request at the first position in the candidate set, whereas a worst-case pre-matcher would not place the matching reference image into the candidate set. Low WAP will lead to a low overall runtime.

Criterion	Improvement over existing pre-matcher	
	Test set 1	Test set 2
Error rate, medium security setting	25 %	31 %
Error rate, high security setting	67 %	38 %
Winner average position, medium security setting	45 %	50 %

Tab.2: *Performance improvement of a fingerprint recognition system with wedge-ring-detector pre-matcher (WRD, as proposed in this article) over the currently used pre-matcher. In all cases, the WRD pre-matcher lead to a drastical improvement of error rates. Furthermore, the winner average position reduced by around 50% and thus halved the overall runtime, since 50% fewer reference images need to be compared in detail by the matcher.*

Results on two distinct test sets (with 950 and 1400 fingerprint images) are listed in Table 2. The quality of the proposed pre-matcher shows up clearly from the strikingly high reduction of error rates. In particular, the reduction of error rates in the high security is remarkable. This high reduction may be explained from the fact that matcher and pre-matcher use independent image features (minutiae vs. spectral energy) and so provide two complementary „views“ of the fingerprint. In particular in a high security setting, matching two complementary views will clearly increase confidence and reduce error rates.

Conclusions

For use in the fingerprint recognition software of the Siemens ID Mouse, we have devised and investigated a simple way of comparing two fingerprint images, based on features derived from the Fourier transform of the image. Details on methodology and an exhaustive list of results can be found in [3].
Using some concepts developed in machine learning, we were able to find a low-dimensional representation of fingerprint images that allows an accurate coarse-level comparison of two fingerprints. While not being sufficiently accurate as a stand-alone system, this coarse comparison turned out to be highly successful as a means of sorting large archives of fingerprints.
Particularly impressive results were obtained when this sorting method was used as the pre-matcher for a traditional fingerprint matcher. On basis of the spectral representation, the pre-matcher selects out of a large archive those fingerprints that are similar to a given request fingerprint. The most similar ones are compared to the request image in detail, using a traditional fingerprint matching method. We were able to improve overall error rates by approx. 30% (depending on the test data set) and reduce the number of required detailed matching operations by 50%. Due to the large performance improvements, the proposed pre-matcher has been fully integrated into the ID Mouse software.

Acknowledgements

This work was done while the author was at Siemens PSE PRO SRT Graz. Fruitful discussions with Kurt Heschgl, Wolfgang Marius, Ernst Haselsteiner, Bernd Wachmann, Josef Birchbauer and Ulrich Haage, as well as the support from Wolfgang Maass and Gerd Hribernig, are greatfully acknowledged.

References

[1] K. Fukunaga. Introduction to Statistical Pattern Recognition. Academic Press, San Diego, CA, 2nd edition, 1990.
[2] B. Schölkopf and A.J. Smola. Learning with Kernels. MIT Press, 2002.
[3] A. Schwaighofer. Fingerprint matching with spectral features. Master's thesis, Institute for Theoretical Computer Science, Graz University of Technology, Austria, May 2000. ■

Dipl. Ing. Anton Schwaighofer, computer scientist, studied Telematik at the TU Graz, currently Ph.D.-student of Prof. W. Maass at Siemens Corporate Technology in München.
Homepage: http://www.igi.tugraz.at/aschwaig

Why Students Don't Ask Questions

Peter Auer
Institut für Grundlagen der Informationsverarbeitung
Technische Universität Graz

Abstract

We analyse the number of questions which a rational student will ask in a learning situation, depending on his or her objective. For this we propose a formal learning model and two possible objectives of the student. In this learning model material is presented to the student in small bits, the student may ask arbitrary yes-no questions about the material, and occasionally the teacher will query the student to access his understanding of the material.

In the first scenario that we will consider, questions asked by the student are regarded as faults. The objective of the student is to minimize the number of questions that he asks plus the number of incorrect answers that he gives to the teacher's queries. The result of our analysis is that in such a scenario a student will ask rather few questions.

In the second scenario the student's objective is to minimize the number of incorrectly answered queries and to be efficient with her learning time. We will argue that there are cases in which a student who asks no questions will need much more time to learn than a student who asks questions.

Introduction

This account on student strategies is an attempt to put results from computational learning theory into a framework which is well known to many of us. In this paper we address a fundamental question: How much better does an active learner acquire information compared to a passive learner. In our model an active learner might ask arbitrary yes-no questions about the material to be learned, whereas a passive learner never asks questions but passively follows the material presented by the teacher. The somewhat surprising result is that an active learner acquires information not much more efficient than a passive learner.

To measure information acquisition we count the number of times the student has to change his concept of the taught material. Fewer changes of concept - until the learned concept is correct - indicate a more efficient acquisition of information. We will show that a passive learner needs to change his concept at most 2.5 times more often than an active learner.

The picture gets very different if we measure the amount of computation needed by active and passive learners[1]. We will provide evidence that in some cases the amount of computation of an active learner might be much smaller than the amount of computation of any passive learner.

In the following section we define our model more precisely and state the relevant results and consequences for student strategies. Then these results are derived for the information oriented view on learning and for the computation oriented view.

The learning model

What to learn

We are interested in a model where a teacher presents some material to a student in an incremental way. We represent such material as a bit sequence $y = \langle y_1, \ldots, y_T \rangle$, $y_t \in \{0, 1\}$, $1 \le t \le T$, of length T. At each step t the teacher gives bit y_t to the student. Before giving y_t to the student the teacher might decide to query the student about y_t. In this case the student has to predict the true y_t by some $\hat{y}_t \in \{0, 1\}$. If $\hat{y}_t \neq y_t$ then the student's prediction was a mistake. We assume that the bit sequence y is not completely arbitrary but that it has some structure. As an example y might be a textbook where expository chapters are followed by exercises and the student is queried only about the solutions of the exercises. We denote by Y the class of all bit sequences with the relevant structure. The student knows about the structure of the taught material, i.e. she knows that $y \in Y$.

Active and passive learners

We will distinguish between active and passive learners. An active learner may ask arbitrary yes-no questions about y at any time. These questions are answered correctly by the teacher. Formally each yes-no question about a property of y can be formulated as „Is $y \in Y'$?" where $Y' \subseteq Y$ is the subset of all sequences in Y with the respective property. A passive learner never asks a question.

Remark: In computational learning theory several similar models are investigated. The maybe most general model in this context considers sequences of input/output pairs $(x, y) = \langle (x_1, y_1), \ldots, (x_T, y_T) \rangle$ where $x_t \in X$ and $y_t \in Y$ for some input domain X and some output domain Y. [2]

Information complexity of learning

As mentioned in the introduction we want to measure the information complexity of a learning task by the number of times the learner changes its concept of the taught material y. Why does this make sense? Because this is the amount of information the learner needs to completely learn y: as long as the learner's concept of y is incorrect she needs another piece of information to change her concept.

A passive learner will change his concept of y after each mistake that he makes, i.e. whenever $\hat{y}_t \neq y_t$. We denote by $M_P(y)$ the number of mistakes of a passive learner P when learning y.

An active learner will change its concept of y not only after a mistake but also after each yes-no question that she asks, since otherwise there would be no need to ask such a question[2] . We denote by $M_A(y) + Q_A(y)$ the number of mistakes plus the number of yes-no questions of an active learner A when learning y.

Remark: We have defined the information

1 Essentially we are measuring the „thinking time" of the learners.

complexity of learning by $M_L(y)$ and $Q_L(y)$, i.e. by the number of mistakes and the number of yes-no questions of a learner L. This circumvents the problem of defining what a „concept" is. A concept is an internal state which usually is not observable, whereas the number of mistakes and questions is easily observable.

Computational complexity of learning

We measure the computational complexity of a learning task by the number of computational steps[3], $C_L(y)$, that a learner L performs when confronted with material y. In our case the computational complexity will depend on the length T of y. We say that L is a computationally fast learner if there is a polynomial p such that $C_L(y) \le p(T)$ for any y of any length T.

Results

The relationship of active and passive learners

The main result in respect to the information complexity of learning is the following theorem.

Theorem 3.1 ([2]) *For any active learner A there is a passive learner P such that for any bit sequence y,*

$$M_P(y) \le \frac{1}{ld(4/3)} \cdot (M_A(y) + Q_A(y)) \le 2.41 \cdot (M_A(y) + Q_A(y)).$$

It says that the information complexity of a passive learner, $M_P(y)$, is at most 2.5 times larger than the information complexity of an active learner, $M_A(y) + Q_A(y)$. The proof of the theorem is given in the next Section.

Our result in respect to the computational complexity of learning relies on a cryptographic assumption. Details of this assumption and the proof of the following theorem are given later in this paper.

Theorem 3.2 *If the RSA cryptosystem is secure than for any $T \ge 1$ there is a class Y_T of bit sequences of length T such that*

1. *there is a fast active learner A with $M_A(y) + Q_A(y) \le \sqrt{T} + 1$ for any $T \ge 1$ and any $y \in Y_T$,*
2. *for any fast passive learner P and any sufficiently large T there is a $y \in Y_T$ such that $M_P(y) \ge T/3$.*

The theorem shows that there are bit sequences which can be learned fast by an active learner but cannot be learned fast, with a similar number of mistakes, by a passive learner. This contrasts Theorem 3.1 which states that, if we do not pay attention to computation time, for any active learner there is a passive learner with a similar number of mistakes.

Remark: Instead of assuming that the RSA cryptosystem is secure the security of other cryptosystems could be assumed. The RSA cryptosystem is for example used in the Secure Socket Layer (SSL) of your internet browser.

Application to student strategies

From Theorem 3.2 it is clear that there are learning task where an active learner can be much more efficient with her „thinking time" than a passive learner. In the following we are interested in the number of questions an active learner should ask if only information complexity is considered. In this model the concern of a student is to minimize the number of questions asked by her (since they are regarded as faults) plus the number of incorrectly answered queries given by the teacher. We assume that the teacher queries a fraction q, say 1%, of all the bits in the taught material y. Then only a fraction q of the mistakes of the student but all the questions asked by the student will be noticed. Thus a rational student L tries to minimize his „costs"

$$\text{cost}_L(y) = q \cdot M_L(y) + Q_L(y).$$

Now we calculate when the costs of an active learner are lower than the costs of a passive learner. From Theorem 3.1 we know that for any active learner A there is a passive learner P with

$$M_P(y) \le 2.41 \cdot (M_A(y) + Q_A(y)).$$

Thus the costs of an active learner are lower than the costs of a passive learner only if

$$\begin{aligned} q \cdot M_A(y) + Q_A(y) &= \text{cost}_A(y) \\ &\le \text{cost}_P(y) = q \cdot M_P(y) \\ &\le 2.41 \cdot q \cdot (M_A(y) + Q_A(y)). \end{aligned}$$

Solving for $Q_A(y)$ we find that an active learner has lower costs only if

$$Q_A(y) \le \frac{1.41 \cdot q \cdot M_A(y)}{1 - 2.41 \cdot q} \approx 1.41 \cdot q \cdot M_A(y),$$

for small q, say $q = 0.01$. This means that a student will ask many questions only if she is queried a lot by the teacher. A little simplified the result can be stated as follows:

A student asks no more questions than he gives wrong answers to queries of the teacher.

This implies a way to encourage students' questions**?!**

Constructing a passive learner from an active learner

In this section we show how a passive learner P can be constructed from any active learner A such that $M_P(y) \le 2.41 \cdot (M_A(y) + Q_A(y))$ for any y. This proofs Theorem 3.1.

The passive learner needs to perform nearly as good as the active learner. For this the passive learner tries to simulate the behavior of the active learner as closely as possible. Since the passive learner does not ask yes-no questions he has to consider both possible answers to a yes-no question asked by the active learner. Each of the two answers might change the behavior of the active learner in a different way. Thus the passive learner has to combine these different behaviors in some sensible way. To achieve this the passive learner gives weights to the different behaviors of the active learner and chooses the behavior with the largest weight. More precisely the passive learner P works as follows:

- The passive learner keeps a list of copies $A_1, \ldots, A_S$ of the active learner A. Each copy corresponds to different answers to the yes-no questions asked so far. This list is initialized with a single copy of A.
- For each copy A_i there is an associated weight w_i. The initial copy of A gets weight 1.
- If any of the copies A_i would ask a yes-no question this copy is split into two copies, one corresponding to the „yes" answer, one corresponding to the „no" answer. The weights of the new copies are both set to half the weight of the original copy A_i.
- If no copy A_i would ask a yes-no question the prediction $\hat{y}_t$ of the passive learner for the next bit y_t is calculated by a majority vote of the A_i according to their weights w_i: Let $\hat{y}_t(i)$ be the prediction of copy A_i for y_t. Then $\hat{y}_t = 1$ if and only if $\sum_{\hat{y}(i)=1} w_i \ge \sum_{\hat{y}(i)=0} w_i$. If the prediction of a copy A_i is correct, i.e. $\hat{y}_t(i) = y_t$, then its weight w_i is not changed. If the prediction is wrong, i.e. $\hat{y}_t(i) \ne y_t$, then the weight is reduced by factor 2, $w_i \leftarrow w_i = 2$.

From a high level view a copy A_i is punished by a factor 1/2 whenever it asks a question or makes

2 The concept could remain unchanged for, say, the „yes answer, and change only for the no answer. Here we take a worst-case point of view by assuming that the answer is always such that the concept is changed.

3 A computational step is performed within a single time unit. Formally, this could be a single CPU clock cycle or a single step of a Turing machine.

a mistake. Since the passive learner P considers all possible answers to yes-no questions, there is one of the copies A_i which has received all the correct answers in respect to the bit sequence y. Thus the weight w^* of this copy is

$$w^* = (\frac{1}{2})^{M_A(y)+Q_A(y)}$$

To calculate the number of mistakes of the passive learner P we consider the sum of the weights w_i, $W = \sum_i w_i$. Initially we have $W = 1$. Clearly W never increases. We calculate how much W decreases after an incorrect prediction of the passive learner, i.e. when $\hat{y}_t \neq y_t$. Since the passive learner predicts as the weighted majority of the copies A_i, we have that in the case of a mistake $\sum_{i:\hat{y}_i(i)\neq y_i} w_i \geq W/2$. Since all the weights in this sum are reduced by a factor 2, we find that W changes as

$$W \leftarrow \sum_{i:\hat{y}_i(i)=y_i} \frac{w_i}{2} + \sum_{i:\hat{y}_i(i)\neq y_i} w_i = W - \sum_{i:\hat{y}_i(i)\neq y_i} \frac{w_i}{2} \leq W - \frac{W}{4} = \frac{3W}{4}.$$

Thus, at the end, $W \leq \left(\frac{3}{4}\right)^{M_P(y)}$. Since $w^* \leq W$ we get

$$\left(\frac{1}{2}\right)^{M_A(y)+Q_A(y)} \leq \left(\frac{3}{4}\right)^{M_P(y)}.$$

Solving for $M_P(y)$ gives

$$M_P(y) \leq \frac{1}{ld(4/3)} \cdot (M_A(y) + Q_A(y)).$$

Learning tasks where asking questions helps

For the construction of learning tasks where asking questions is helpful we assume the existence of cryptographically strong pseudo-random bit generators. Such cryptographically strong pseudo-random bit generators exist, for example, if the RSA cryptosystem is secure [Blum and Micali, 1984, Alexi et al., 1984]. We use cryptographically strong pseudo-random bit generators as functions f_n, $n \geq 1$,

$$f_n : \{0,1\}^n \rightarrow \{0,1\}^{n^2},$$

such that

1. for any input x the output $f_n(x)$ can be computed fast,
2. for a random input x the output $f_n(x)$ „looks“ random.

We say that the output $f_n(x)$ looks random if, for unknown x, no single bit of the output $f_n(x)$ can be computed fast even if all remaining bits of $f_n(x)$ are known[4].

There is strong emphasis on the fact that no *fast* computation is possible since a „slow“ computation is still possible: one could search exhaustively for the input x such that $f_n(x)$ matches the known bits. But such an exhaustive search would require 2^n computation time.

Using the functions f_n we construct the classes of bit sequences Y_{n^2} as

$$Y_{n^2} = \left\{ f_n(x) : x \in \{0,1\}^n \right\}$$

Then for any $y \in Y_{n^2}$ an active learner A can ask about the corresponding x with $f_n(x) = y$ using n yes-no questions. Knowing x the active learner will make no mistakes, hence $Q_A(y) = n$ and $M_A(y) = 0$. By the properties of the functions f_n a fast passive learner cannot compute a single bit of $f_n(x)$. Thus a fast passive learner can only guess the bit sequence y and will make more than $n^2/3$ mistakes.

Remark: It is quite illustrative to see how the passive learner described in Section 4 would simulate the above active learner. At the beginning the active learner asks n questions to find the correct x. Thus, by n splits, the passive learner gets 2^n copies of the active learner. Then the passive learner predicts with the weighted majority of these copies. Each time a copy predicts incorrectly its weight is reduced by factor 2. In very short time the weight of the right copy dominates all other weights because the right copy never predicts incorrectly. Thus the passive learner makes only a little more than n mistakes, but his „thinking time“ is much larger than that of the active learner since he has to deal with 2^n copies of the active learner.

Acknowledgment

Most of this work was done with Phil Long when he was visiting Graz. I hope he has as good memories of this time as I have.

I also gratefully acknowledge support from the ESPRIT Working Group in Neural and Computational Learning II, NeuroCOLT 2 27150.

References

[1] Alexi, W., Chor, B., Goldreich, O., and Schnorr, C. P. (1984). RSA/Rabin bits are 1/2+ 1/poly(log n) secure. In 25th Ann. Symp. Foundations of Computer Science, pages 449-457. IEEE Computer Society Press.

[2] Auer, P. and Long, P. M. (1999). Structural results about on-line learning models with and without queries. Machine Learning, 36:147-181. A preliminary version has appeared in Proceedings of the 26th ACM Symposium on the Theory of Computing.

[3] Blum, M. and Micali, S. (1984). How to generate cryptographically strong sequences of pseudo-random bits. SIAM Journal on Computing, 13(4):850-864. ■

4 The definition given here is a little sloppy. For formal details see [1].

Prof. Dr. Peter Auer, computer scientist and mathematician (expert for probability theory), Ph.D. on software technology at the Technische Universität Wien, since 1997Associate Professor at the Institut für Grundlagen der Informationsverarbeitung der TU Graz.
Homepage: http://www.igi.tugraz.at/pauer

Resource Allocation and the Exploration-Exploitation Dilemma

Nicolò Cesa-Bianchi
Department of Information Technologies
University of Milan, Italy

Introduction

Suppose an indivisible resource is scheduled among N users. However, users may or may not exploit the resource once they get it. Let $x_{i,t} \in \{0, 1\}$ denote whether or not user i would exploit the resource should he get it at time t, where $t = 1, 2, \ldots$ (for simplicity, we assume time is discretized). Your goal is to maximize the overall exploitation of the resource over a certain timespan. That is, your goal is to choose a schedule $i_1, i_2, \ldots, i_T$ of the resource among the N users maximizing $x_{i_1,1} + x_{i_2,2} + \ldots + x_{i_T,T}$. This is usually known as the „multiarmed bandit problem“ (in U.S. slot-machines are appropriately called „bandits“, and our resource allocation task may be viewed as the problem of spending T tokens on N different slot machines - a N-armed bandit - with the purpose of maximizing the overall win). The multiarmed bandit is a prototypical example of a trade-off between exploration and exploitation. The key aspect of the problem is that while we can observe the exploitation made by the user to which we assigned the resource at time t, nothing is known about what the other users would have done if they were given the resource at the same time. Equivalently, using our notation, at each time t we only observe $x_{i_t,t}$ and know nothing about $x_{k,t}$ for all $k \neq i_t$. Therefore, if at time t we assign the resource to the user which has the best exploitation record so far (i.e. the user j for which the running sum $x_{j,1} + \ldots + x_{j,t-1}$ is highest), we may fail to discover that some other user would now exploit the resource much better than user j. The classical way [5] to model the user exploitation $x_{i,t}$, which we will henceforth call simply „reward“, is to assume that they are realizations of independent and identically distributed Bernoulli random variables $X_{i,t}$. That is, $\mathsf{P}(X_{i,t} = 1) = \mu_i$ for some fixed quantity $0 \leq \mu_i \leq 1$. In this model, the goal is to maximize the sum of rewards by choosing, as often as possible, the user j with the highest reward expectation μ_j among $\mu_1, \ldots, \mu_N$. The strategy used to choose a user based on all past observed rewards is called an *allocation policy*. The goodness of a policy is measured by its expected *regret at horizon T*, defined by

$$\left(\max_{1\leq i\leq N} \mu_i\right) T - \mathsf{E}\left[\sum_{t=1}^{T} X_{i_t,t}\right].$$

Hence, the regret measures how much the allocation strategy lost, on average, for not always keeping the resource with the user having the highest reward expectation. Lai and Robbins were the first ones to show that the expected regret for the optimal policy must eventually grow logarithmically in the size T of the horizon [4]. These policies typically work by estimating the reward expectation of each user via upper confidence bound estimators. We now give an example of such a policy. Let $\overline{X}_{i,t}$ be the sample average for the reward of user i at time t, and let $S_{i,t}$ be the number of times user i was given the resource in the first t time steps. Then, at time $t + 1$, the policy chooses user k maximizing the index

$$C_{k,t} = \overline{X}_{k,t} + \sqrt{\frac{\alpha \ln t}{S_{k,t}}}$$

where $\alpha > 0$ is a parameter. The idea behind this policy is very simple. For Bernoulli independent random variables $X_{k,1}, X_{k,2}, \ldots$, Chernoff-Hoeffding bounds [3] state that

$$\mathsf{P}\left(\overline{X}_{k,t} + \sqrt{\frac{\ln t}{2S_{k,t}}} < \mu_i\right) \leq \frac{1}{t}.$$

This ensures that the index $C_{i^*,t}$ of the overall best user i^* (i.e. such that $\mu_{i^*} \geq \max_j \mu_j$) is smaller than the user's true expected reward μ_{i^*} with probability at most $1/t$. This is in turn used to show that a nonzero regret at time t occurs only with probability $1/t$. When summed over T trials, this bound yields the desired logarithmic regret (see [1] for a detailed proof).

The logarithmic regret is the best that can achieved when the reward probabilites are constant independent of the horizon. On the other hand, if the reward probabilities are allowed to depend on the horizon, then the regret can be much higher. Suppose that N-1 users exploit the resource with proability 1/2 and one (unknown) user exploit the resource with probability $1/2 + \varepsilon$ for some small $\varepsilon > 0$. Now, if ε is chosen sufficiently small with respect to T, i.e. $\varepsilon \approx \sqrt{N/T}$, then *any* allocation policy will suffer in T rounds a regret of order $\sqrt{TN}$ (see [2] for a proof of thispfact). Hence, whenever the reward probabilities may depend on T, then the best achievable regret is of order $\sqrt{T}$. In the next section we will describe an allocation policy that achieve this square-root regret also in a nonstochastic bandit setting. In particular, we will describe allocation policies with square-root regret even in the case where the rewards are not i.i.d. random variables, but they are chosen deterministically in a totally arbitrary (and thus possibly malicious) way.

The worst-case model

We introduce a worst-case bandit model parametrized by a finite number $N > 1$ of users and by an unknown reward assignment specifying, for each $1 \leq i \leq N$ and for each $t \geq 1$, the deterministic reward $x_{i,t} \in \{0, 1\}$ obtained by assigning the resource to user i at time t (see [2] for an extensive analysis of this model). At each time t, we only know the rewards $x_{i_1,1}, \ldots, x_{i_{t-1},t-1}$ obtained in the past. After user i_t obtains the resource, we observe the reward $x_{i_t,t}$ according to the underlying reward assignment. We will use $G = x_{i_1,1}, \ldots, x_{i_T,T}$ to denote the total reward at horizon T of a given allocation policy and $G_{\max}$ to denote the total reward at horizon T of the best user, i.e. $G_{\max} = \max_{1\leq i\leq N} (x_{i,1} + \ldots + x_{i,T})$. As

our allocation policies are randomized, they induce a probability distribution over the set of all user sequences $(i_1, i_2, \ldots)$.. We will use $\mathrm{E}[G]$ to denote the expected return of such a randomized policy, where the expectation is taken with respect to the induced distribution. Our main measure of performance for a policy is the *expected regret* against the best user, defined by $G_{\max}$-$\mathrm{E}[G]$.

We now describe our randomized allocation policy Exp3 and give bounds on its performance. The randomized policy Exp3 maintains a weight $w_{i,t}$ for each user $i = 1,\ldots,N$. Initially, the weights are set to 1, i.e. $w_{i,1} = 1$ for all i. At each time $t = 1,2,\ldots$ a user i_t is drawn according to the distribution $p_{1,t}, \ldots, p_{N,t}$ assigning to user i probability

$$p_{i,t} = (1-\gamma)\frac{w_{i,t}}{\sum_{j=1}^{N} w_{j,t}} + \frac{\gamma}{N}$$

where $0 < \gamma \leq 1$ is an input parameter. Let $x_{i_t,t}$ be the reward received. Then, the weights are updated as follows: For $j = 1,\ldots,N$ set

$$\hat{X}_{j,t} = \begin{cases} x_{j,t}/p_{j,t} & \text{if } j = i_t \\ 0 & \text{otherwise} \end{cases} \qquad (1)$$
$$w_{j,t+1} = w_{j,t}\exp\left(\gamma \hat{X}_{j,t}/N\right).$$

Note that $\hat{X}_{i,t}$ is an unbiased estimate of the actual reward $x_{i,t}$. In fact, $\mathrm{E}[\hat{X}_{i,t} | \mathrm{I}_1, \ldots, \mathrm{I}_{t-1}] = x_{i,t}$ where the expectation is conditioned on the outcomes of the past t-1 randomized user draws. Note further that $w_{i,t} = \exp(\gamma(\hat{X}_{i,1}+\ldots+\hat{X}_{i,t-1}/\mathrm{N})$. This shows how the probabilities $p_{i,t}$ address the exploration/exploitation trade-off by first assigning to each user a probability $w_{i,t}/\left(\sum_{j=1}^{N} w_{j,t}\right)$ exponential in the estimated current return for the user (exploitation), and then mixing this probability with the uniform distribution 1/N over all users (exploration). The tuning of the mixing coefficient γ will turn out to be crucial. We now state an upper bound on the expected regret of Exp3 that holds for each choice of the parameter γ.

Theorem 1 *For any $N > 0$ and for any $\gamma \in (0, 1]$, the expected regret G_{max}-$\mathrm{E}[G]$ of algorithm* Exp3 *is at most $2\gamma G_{max} + (N \ln N)/\gamma$ for any reward assignment and for any $T > 0$.*

A suitable tuning of γ reveals that the regret of Exp3 comes close to the lower bound $\sqrt{TN}$ that any allocation policy must incur in this model.

Corollary 2 *For any $T > 0$, suppose that* Exp3 *is run with input parameter $\gamma = \sqrt{(N \ln N)/(2T)}$ (where γ is set to 1 if the above value is larger than 1). Then, for any reward assignment the expected regret G_{max}-$\mathrm{E}[G]$ of algorithm* Exp3 *is at most $2\sqrt{2TN \ln N}$.*

Regret against arbitrary schedules

So far we have bounded the policy's regret for not always choosing the single globally best user, i.e. the user i maximizing $x_{i,1} + \ldots + x_{i,T}$. More generally, one could also bound the regret for not choosing a particular schedule of users $j^T = (j_1, j_2, \ldots, j_T)$. Bounding the regret simultaneously with respect to all user schedules, with no restrictions, is clearly hopeless. Yet, we can get a result by allowing the regret to scale with a quantity measuring the „hardness" of the schedule. A good definition for hardness of a schedule j^T is $1+n$, where n is the number of times the resource is moved from a user to a different one in the order given by the schedule. Let $G_{j^T} = x_{j_1,1} + x_{j_2,2} + \ldots + x_{j_T,T}$ be the return at horizon T of an arbitrary sequence $j^T = (j_1, j_2, \ldots, j_T)$. We want to upper bound G_{j^T}-G irrespective to the underlying reward assignment. If the hardness of j^T is S, then we can think of partitioning j^T in S consecutive segments so that the user who has the resource does not change within each segment. For example, if $T = 6$ and $j^T = (3, 3, 1, 1, 1, 1)$, then the hardness of j^T is 2 and we partition it in segments (3, 3) and (1, 1, 1, 1). Now we can measure the regret of Exp3 within each segment just as we did in Theorem 1 and then sum up the regrets over the segments. However, for technical reasons, we need to slightly alter Exp3 by replacing the weight update step (1) with

$$w_{j,t+1} = w_{j,t}\exp\left(\gamma \hat{X}_{j,t}/N\right) + \frac{\alpha}{N}\sum_{i=1}^{N} w_{i,t}$$

where α is a new input parameter. This amounts to sharing among all weights a fraction α/N of the total weight. This argument leads us to prove a regret bound of the form $S\sqrt{TN \ln N}$ where S is the hardness of j^T. This bound holds uniformly over *all* schedules j^T of users. If one wants a result that holds for a set of schedules of hardness at most S', then, by tuning α in terms of S', the above bound improves to $\sqrt{S'TN \ln N}$.

References

[1] P. Auer, N. Cesa-Bianchi, and P. Fischer. Finite-time analysis of the multiarmed bandit problem. Machine Learning, 23(2/3):235~256, 2002.

[2] P. Auer, N. Cesa-Bianchi, Y. Freund, and R.E. Schapire. The non-stochastic multi-armed bandit problem. Submitted for publication, 2002. A preliminary version appeared in: Proceedings of the 36th Annual Symposium on the Foundations of Computer Science. IEEE press. pp. 322~331, 1995.

[3] H. Chernoff. A measure of asymptotic efficiency for tests of a hypothesis based on the sum of observations. Annals of Mathematical Statistics, 23:493~507, 1952.

[4] T.L. Lai and H. Robbins. Asymptotically efficient adaptive allocation rules. Advances in Applied Mathematics, 6:4~22, 1985.

[5] H. Robbins. Some aspects of the sequential design of experiments. Bullettin of the American Mathematical Society, 55:527~535, 1952. ■

Prof. Dr. Nicolò Cesa-Bianchi, computer scientist and mathematician, Associate Professor at the University of Milan, Italy.
Homepage: http://homes.dsi.unimi.it/~cesabian

A Very Short Story About Autonomous Robots

Gerald Steinbauer[*], *Roland Koholka*[#], *Wolfgang Maass*[*]
[*] *Institut für Grundlagen der Informationsverarbeitung, Technische Universität Graz*
[#] *KNAPP Logistik Automation GmbH, Graz*

Abstract
Machine learning for autonomous mobile robots is a very interesting but also very difficult problem. In this domain you need robust, fast and efficient learning algorithms. The combination of machine learning and mobile robots allows us to create machines whose performance surpasses both explicitly programmed robots and humans. Although humans can learn, their sensors and actuators are in several aspects inferior to those of robots. On the other hand a non-learning robot can only perform tasks where all the individual difficulties and complexities can be anticipated by the programmer of the robot.
In this short article we discuss both a completed project, and a new one that has just started. The first project produced a robot that applied learning to improve his minigolf skills. The new project is the creation of the first Austrian team of autonomous robot soccer players that will compete in the robot soccer world championship RoboCup[1].

Machine learning for real robots

If you work on machine learning for real robots you may ask yourself why machine learning for real robots is so much more difficult than for other applications, such as simulated robots, optimization or classification. There are three main reasons for that. First, everything in the real world is nondeterministic and noisy. You could not rely absolutely on what the sensors of the robot perceive or on what the actuators of the robot may do. For that reason the learning algorithms have to be robust against this insufficiency of the robot. The second reason is that most machine learning methods require hundreds or thousands of training examples. But a real robot cannot have the luxury of training for weeks or months. The third reason is the limited computing power of a mobile robot. It is not very satisfying if a robot stops for ten minutes in order to think about its next decision. Hence, extremely efficient learning algorithms are needed. All these problems have their own charm, but they can also be very frustrating in the end. In spite of all this, the work with machine learning and real robots is quite rewarding. To see a robot show a surprising accurate behavior for a certain task, where explicit programming of such behavior was nearly impossible, is very satisfying.

From Robot Minigolf ...

In the earlier project with real robots we worked on a task for an autonomous robot that requires learning insofar as a solution of this task by a non-learning robot is inconceivable (see [1]). On the other hand this task is also too difficult to be solved by a human. People can learn, but they do not have the mechanical skills which this task requires. The task had been posed in the form of a student competition at the Technische Universitaet Graz. It can be outlined as follows. A 2x5 m white platform – surrounded by a black wall – had been divided by a black line into a release zone of about 1 m length and a target zone of about 4 m length (see Figure 1). For each instance of the task one out of a large variety of green colored hills was placed at an arbitrary position – but at least 40 cm away from all walls – into the target zone. The hills were formed out of different kinds of hardening or non-hardening resins. These hills had a relatively rough surface and all kinds of odd shapes (diameters 30-60 cm), but they all had a round dip on the top of about 2 cm depth, with diameters ranging from 8 to 12 cm. The task was to accelerate and release a red billiard ball (diameter 5 cm, weight 142 g) in the release zone on the left part of the platform so that it comes to rest in the dip on top of the hill. To solve this task, the ball had to be released with just the right speed v and angle α. For most hill positions the set of parameters $\langle v, \alpha \rangle$ that solved the task was so small that even an experienced human typically needed 40 or more trials before the first successful shot. The number of trials needed for a second successful shot was not significantly smaller, indicating that in spite of all experience a human can solve this task essentially just by chance.
After each unsuccessful trial the robots in the competition had to find the ball, move it back to the release zone, and initiate the next shot. All this – just as the trials themselves – had to be done completely autonomously, using only on-board sensors, computing devices and power

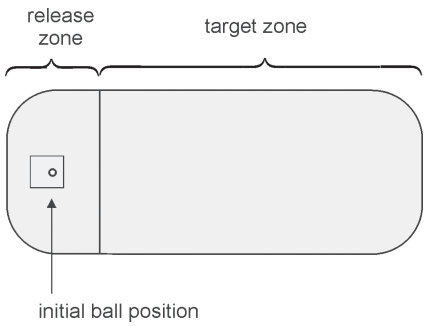


Fig.1: *The minigolf playfield.*

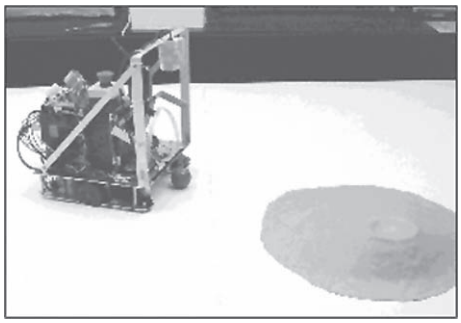


Fig. 2: *Robot Oskar while recapturing the ball.*

1 This project is partially supported by Knapp Automation and Logistics, Siemens AG, and JUMPtec.

supply. There were no interventions from the outside allowed. The performance measure for the competition was the total time needed by a robot until he had succeeded three times for the current hill and hill-position, averaged over a fair number of different hills and hill-positions.
The winner of the competition was the robot Oskar (see Figure 2) because of its simple and reliable hardware/software design and its fast and robust learning algorithm. Oskar moves via a differential drive powered by stepping motors. This enables Oskar to reposition himself very precisely in the release zone using visual markers (±1mm displacement, 0.2° angle error). This fact is important for a meaningful interpretation of successive failed trials, as well as for producing repetitions of successful trials. Oskar uses two cameras as its main sensors. One camera looks ahead (used mainly for ball tracking), the other camera looks orthogonally down in front of the robot (used mainly for obstacle avoidance). Oskar accelerates the ball by hitting it with a hammer that can be pulled up to variable heights, thereby allowing control over the initial speed *v* of the ball. Oskar catches the ball by lowering a flexible „lasso". He transports the ball back into the bay in front of the hammer with a cute body movement initiated by his two wheels („hip swing"). For further details about Oskar see [2], [1], and [W1].

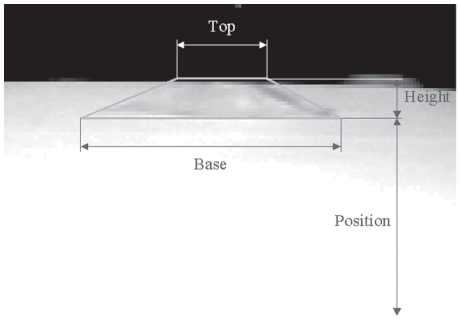


Fig.3: *A typical hill, as seen by the onboard camera of Oskar. The trapezoid approximation provides the inputs for the neural network.*

The learning of Oskar is implemented as follows. Oskar uses both a longterm- and a shortterm learning algorithm. In order to compute the initial speed *v* for a new instance of the task he uses longterm learning via a sigmoidal neural network (MLP) with 4 hidden units. This neural network absorbs memory from positive experiences in the past. The inputs to the neural network are the coordinates of the 4 corner points of a trapezoid (see Figure 3) that approximates the segmented video image of the hill, recorded from the starting position. The neural network is trained via backprop, with training examples provided by preceding successful trials. The neural network started to make useful predictions for an appropriate initial speed *v* after it was trained with data from 60 successful trials.
The other parameter a for the first trial on a new hill is simply computed by aiming at the center of the upper horizontal line segment („Top") in the trapezoid that approximates the hill. Since Oskar's first trial is likely to succeed only for very simple hills, the key point of his operation is his capability to learn via shortterm learning autonomously from preceding unsuccessful trials for the same instance of the task. The shortterm learning is inspired by the two principles of „trial and error" and the classical binary search. From the mathematical point of view it is a two-dimensional searching problem.
First Oskar draws the trajectory of the ball for each shot (the trajectory is extracted from camera images recorded during the shot). Then he classifies the trajectory by a hand-optimized, heuristic classification algorithm into one of the following classes:

1. ball went too much to the right
2. ball went too much to the left
3. ball reached the dip, but went through it
4. ball rolled back from the hill
5. success
6. anything not fitting into classes 1-5

This classification is used as a feedback for the binary search, although it can be erroneous due to insufficiencies of the image processing and the classification algorithm. Therefore we had to adapt the classical binary search to be robust against erroneous feedback. This robustness is

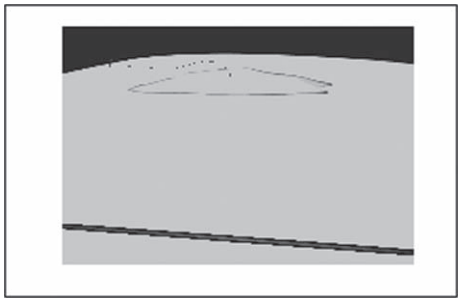


Fig.4: *Typical trajectory, classified to class 2.*

achieved by extra mechanisms. In contrast to the ordinary binary search, we halve the search interval only if we see „opposite" classification pairs (class pair 1/2 or class pair 3/4) in successive trials. Furthermore, in some cases the search interval may be doubled again, enabling a recovery after erroneous answers. Fortunately each of the two classification pairs is relevant for just one of the two binary searches. The classification pair 1/2 triggers the binary search for the angle a. The classification pair 3/4 triggers the binary search for the velocity *v*. In case of classification 5 and 6 neither the angle a, nor the velocity *v* are changed. In the latter case we are not able to extract a relevant feedback. In the former case we have already found a solution. Furthermore, if this solution is stable enough, it provides a new training example for long term learning. This mechanism collects positive experiences for the robot. An exact description of the learning algorithm can be found in [1] and [2].
This simple learning algorithm works surprisingly fast and robust for the given task. Oskar needs about 1 to 8 trials for various hills and positions, while humans need about 40 trials for the same task. Oskar's hardware is also very robust because of its simple design. He had been running continuously 9 hours a day during 6 months of a major exhibition, the Steiermaerkische Landesausstellung in Graz. Currently Oskar is part of the permanent collection of the famous Ars Electronica Center in Linz [W2] and he is still working every day (Sundays included).

... to Robot Soccer

After our robot Oskar had learned to play minigolf, we got a little bored. So we got interested in a new sport for our robot, namely robot soccer. We decided to design and build a team of new autonomous mobile robots, that are able to compete in the RoboCup Middle-Size League World Championship 2003 in Padua, Italy. Since a wide range of knowledge is needed to build a team of autonomous mobile robots, many institutes of the Technische Universitaet Graz are involved in this project. A complete list can be found on the project's homepage [W3].

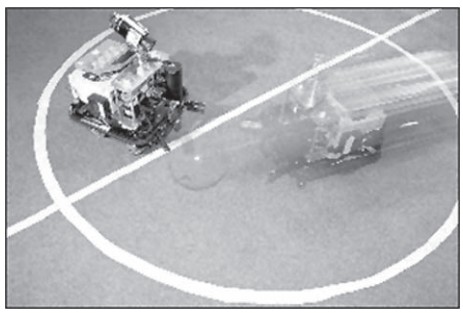


Fig.5: *Players of the GMD Middle Size League Team.*

The Robot World Cup Initiative [W4] is an attempt to foster artificial intelligence and intelligent robotics research by providing a standardized problem that poses a tough challenge for several scientific disciplines and technologies. The first RoboCup competition [3]

was held 1997 at the IJCAI in Nagoya. The interest in RoboCup and the number of participating teams increases every year. Until a robot team is actually able to perform a soccer game, various technologies have to be incorporated, including multi-agent cooperation, strategy acquisition, real-time reasoning, machine learning, robotics, and sensor-fusion. Contrary to other robots, which are optimized for a single heavy-duty task, robot soccer is a task for a team of cooperative fast-moving robots in a dynamically changing environment. The RoboCup is organized into several leagues. They differ in several aspects: simulated or real robots, the types of sensors (global or individual), and the size of the robots. So everybody can find the optimal platform for their research.

The games in the simulation league run on the RoboCup soccer server [W5] which is accessible by the public. The RoboCup soccer server provides a standard platform for research on multi-agent systems. The soccer server simulates the player, the ball and the field for a 2D soccer match. Up to 22 clients (11 for each team) connect to the server, each client controlling a single player. The client sends low level commands (dash, turn or kick) to be executed (imperfectly) by the simulated player he is controlling. The soccer server simulates the (imperfect) sensing of the player, sending an abstracted interpretation to the clients. This league has already reached a high level in intelligent behavior, learning, and team play [4].

Small-size robot teams consist of up to 5 robots, with each robot fitting into an area of 180 cm^2.

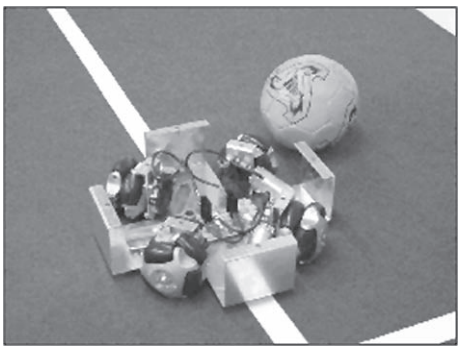


Fig.6: *The prototype of our driving unit.*

The robots play on a green-carpeted table-tennis-sized field with sloping walls. The rules permit a camera to be fixed above the field and connected with an off-field computer for a global vision system. This system is used to track the players, the opponents and the ball. During the game the robots use wireless communication to receive tracking information from the off-field computer, as well as commands or strategic information. No human intervention is allowed except for interpretation of the referee's whistle. The teams in this league have developed interesting strategies for cooperative behavior, but they are still not at the level of the simulation league.

In the middle-size RoboCup league, teams of four roughly 50x50x80cm sized robots compete. The field size is currently 9m x 5m. The major difference to the small-size league, in addition to the size of the robots and the field, is that no global vision of the field is allowed. Thus the robots have to rely totally on their own sensors, including vision. The robots are fully autonomous, i.e., their sensors, actuators, power supply and computational power are on-board, and no external intervention by humans is allowed, except to insert in or remove robots from the field. External computational power is allowed, although most teams do not use it. Wireless communication between the robots and/or with the external computer is also allowed. As in most of the other leagues, relevant objects are distinguishable by their color: the ball is orange, the goals are yellow and blue, the robots are black, the walls are white, the robot markings (to distinguish the teams) are magenta and light blue. The middle-size league provides a serious challenge for research disciplines such as multi-robot cooperative teams, autonomous navigation, sensor fusion, vision-based perception, and mechanical design, to name only a few.

In the last year the community has decided to remove the walls around the field for the middle-size league, as another step towards a more realistic soccer game. Since now the ball and also the robots are able to leave the field, the demands on the robots regarding ball handling, perception, and strategy increase. This may be a realistic chance for a new upcoming team to participate successfully, because also the established teams have to change their paradigms.

Currently artificial intelligence and machine learning do not yet play in this league such an important role as, e.g., in the simulation league. The problems caused by perception (mainly vision), self-localization, mechanical and electronic design (ball handling and robot drives) are still dominating, and make it more difficult to implement adaptive, intelligent, and cooperative behavior.

In view of this fact we have divided our RoboCup project into two sections, which hopefully will meet each other again in the end. One section is working on a new powerful robot platform, which should provide optimal perception and optimal dynamics for playing soccer, because commercial robot research platforms are still not optimal for playing soccer. By studying games that were played during official tournaments in the last year, we saw that a platform which is fast and flexible in movement is very important for a successful dynamic soccer play, and provides a chance to outperform the opponents. So the main design goal for our platform is the development of a fast omni-directional driving unit. In the 4th Robotic Soccer World Championship in Melbourne in 2000 the Golem Team [5] from the University of Padua showed an omni-directional drive for their robots with three universal wheels, each driven by a separate DC Motor, mounted at the vertexes of an equilateral triangle. This arrangement allows the robot to control all three degrees of freedom in the plane ($\Delta x, \Delta y, \Delta\varphi$) simultaneously. In order to increase the stability of the robot platform, especially during a rough soccer play, we adapt this configuration to a model with four wheels. Our configuration of the four motors and wheels is shown in Figure 6. The other section is working on a simulator for the upper platform, an adaptation of the Webots simulator [W6], which should give us the opportunity to implement and investigate high-level behaviors and learning approaches even before the real platform has reached a final stable state (only the kinematics and sensor inputs of the robot must be known in advance). This gives us the possibility to simulate and study higher level behavior and machine learning algorithms on our platform in a sufficient realistic manner while we are still working on the implementation of the real platform. We hope that we can transfer higher level strategies and learned behaviors back to the real robot platform.

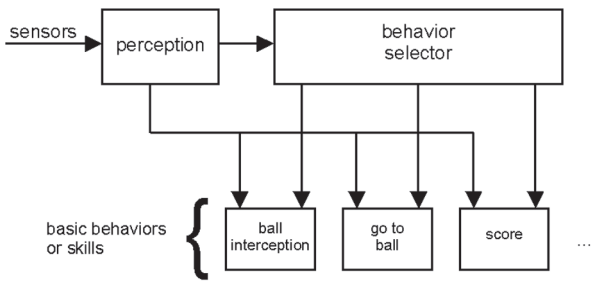


Fig.7: *Agent architecture of our soccer robots.*

Since we are now at a very early stage in the project, our currently used agent architecture is quite simple but easy to handle and to understand (see Figure 7). It consists of a perception module, a behavior selector and a set of basic behaviors or skills. The perception module processes all sensory inputs (mainly vision and odometry) and provides a model

of the state of the robot and its environment (mainly the position of all the robots and the ball). Based on this state information the behavior selector selects one behavior from a given set of behaviors or skills which the robot is able to perform. The selected behavior is executed for a given short period of time. The set of the basic behaviors consists of very fundamental skills the robot can perform.

This architecture has three main advantages. First, it is simple to understand and to implement, which is very important in view of the early state of the project in order to get a feeling for the potential of our platform. Second, the robots have only to provide a small set of „primitive" behaviors or skills. By having the behavior selector combine these basic behaviors a relatively complex overall behavior could be achieved. This approach builds on the subsumption architecture by R. Brooks [6]. The behavior selector is currently designed and optimized by hand. The third advantage is that the simple basic behaviors or skills can also be learned and autonomously optimized by the robot, using for example reinforcement learning. This approach is discussed in the book of P. Stone [4] for the simulation league.

Conclusion

We have tried to show that the work with autonomous mobile robots and machine learning for such robots is difficult, sometimes frustrating, but most of the time fascinating and satisfying. With the robot Oskar we had demonstrated that the combination of machine learning and a simple robust robot platform may be able to fulfill tasks where humans fail. This was a very surprising experience to us. Finally, we hope that we will be able to transfer the „spirit" and the success of Oskar to our new robot soccer team.

References

[1] W. Maass, G. Steinbauer, and R. Koholka. Autonomous fast learning in a mobile robot, to appear 2002 in: *Lecture Notes in Computer Science*, Springer-Verlag.

[2] Gerald Steinbauer. *Machine Learning for an Autonomous Mobile Robot*. Diploma thesis. Technische Universitaet Graz, Institute for Theoretical Computer Science, 2001.

[3] H. Kitano, editor. *RoboCup-97: Robot Soccer World Cup I*. Number 1395 in Lecture Notes in Artificial Intelligence. New York: Springer, 1998.

[4] Peter Stone. *Layered Learning in Multiagent System: A Wining Approach to Robotic Soccer*. The MIT Press, 2000.

[5] Paolo de Pascalis et al. *Golem team in middle-sized robots league*. In RoboCup 2000: Robot Soccer World Cup IV. Number 2019 in Lecture Notes in Artificial Intelligence. Springer, 2001.

[6] R. A. Brooks. *A robust layered control system for a mobile robot*. IEEE Journal of Robotics and Automation, Vol. 2, No. 1, March 1986, pp. 14-23.

Links

[W1] http://www.igi.tugraz.at/maass/robotik/ oskar: The Homepage of the robot Oskar.

[W2] http://www.aec.at: Ars Electronica Center, Linz, Austria.

[W3] http://www.robocup.tugraz.at: The RoboCup Project of the Technische Universitaet Graz.

[W4] http://www.robocup.org: The RoboCup Federation.

[W5] http://sserver.sourceforge.net/NEW/: The RoboCup Soccer Server.

[W6] http://www.cyberbotics.com/webots/: The Webots Robot Simulator. ■

Dipl. Ing. Gerald Steinbauer, computer scientist, studied Telematik at the Technische Universität Graz, together with Dipl. Ing. Roland Koholka winner of the first robot competition 1995 of the IEEE-Student Branch at the TU Graz, and of the robot competition *Robotik 2000* at the TU Graz, heads together with Dipl. Ing. Roland Koholka the development of a RoboCup team at the TU Graz.

Dipl. Ing. Roland Koholka, computer scientist, currently at Knapp Logistik GmbH, studied Telematik at the Technische Universität Graz, together with Dipl. Ing. Gerald Steinbauer winner of the first robot competition 1995 of the IEEE-Student Branch at the TU Graz, and of the robot competition *Robotik 2000* at the TU Graz, heads together with Dipl. Ing. Gerald Steinbauer the development of a RoboCup team at the TU Graz.

Prof. Dr. Wolfgang Maass, computer scientist and mathematician, Ph.D. under Prof. K. Schütte (Mathematical Logic) at the University of Munich, 1986-1991 Professor at the University of Illinois (Chicago), since 1991 Professor at the TU Graz, since 1992 Head of the Institut für Grundlagen der Informationsverarbeitung der TU Graz. Homepage: http://www.igi.tugraz.at/maass

A Bioinformatics Problem Motivated by Analysis of Gene Expression Data

Philip M. Long
Genome Institute of Singapore

Recent technological advances have dramatically increased the rate at which a variety of different kinds of data related to molecular biology are being generated. There appear to be a wealth of opportunities to gain insight into how cells work by analyzing existing data, and these opportunities seem to be expanding faster than they can be pursued. In this note, I would like to tell you about one problem that I have encountered in analyzing a particular kind of data.

First, please allow me to remind you of some of the basics of molecular biology. DNA can be thought of as long strings composed of letters chosen from a four-letter alphabet. Substrings, called genes, can be viewed as encodings of proteins, which are large molecules that do the work of the cells. Proteins do a wide variety of different things, including forming scaffolds that help a cell keep its shape, acting as a medium to store aspects of the state of the cell, acting as sensors to receive signals from outside the cell, protecting DNA from the environment, and so on. Most often, the protein associated with a gene is not continuously manufactured; instead, a region in DNA near the region coding for the protein acts as a switch, and some molecule must trip that switch to signal the protein to be made. When this happens, we say that the gene is being expressed.

Microarrays allow scientists to measure the extent to which a large number (at present over 10000) of different genes are expressed in a given tissue at a given point in time. The expression levels are referred to collectively as the *expression profile* of the tissue.

One way that microarray technology has been applied is to compare the expression profiles of diseased and normal tissues to try to gain clues as to what genes are involved in the disease process. A goal for bioinformatics to support such research can be framed as follows. Suppose scientists are investigating a particular disease, say a kind of cancer. We wish to model the question of finding all genes that might be affected when tissue has this cancer. Suppose we model the generation of a list of expression profiles as follows. Some joint probability distribution governs the expression profile of a tumor tissue, and a different probability distribution governs the expression profile of normal tissue. The problem is, given random examples of tumor and normal tissues generated this way, with high probability, find the smallest set of genes S for which the collective behavior of the rest of the genes is the same in tumor and normal tissues. Specifically, if new expression profiles were measured using only the genes other than S, then the probability distributions governing the distributions of these new expression profiles for tumor and normal tissues respectively would be the same.

The main approaches to finding genes involved in a disease process using microarray data appear to systematically miss genes for two different reasons. The first approach looks for genes whose individual expression levels are different between the diseased and normal tissues (see [1]). It appears that this approach might miss occasions where the collective behavior of groups of genes triggers disease. As a very artificial example for illustrative purposes, suppose that

- 11 genes are expressed to only one of two degrees, a lot or a little,
- both were equally likely, and
- that if a majority of the 11 were expressed a lot, then disease was present.

Then any particular gene would be expressed a lot in diseased tissue with probability only

$$\frac{\sum_{i=5}^{10}\binom{10}{i}}{\sum_{i=6}^{11}\binom{11}{i}} \approx 0.623$$

difficult to differentiate from 1/2 using a small collection of tissues, particularly when you need to guard against false positives potentially arising from thousands of irrelevant genes.

A second approach is based on work in Machine Learning on feature selection. The algorithms for this that I have seen applied to microarray data (see [2, 3]) look for small collections S' of genes for which a rule can be constructed using the levels of expression of the genes in S' that accurately discriminates between tumor and normal tissues. For example, a rule might say that if the level of expression of G_{17} is at most 10 and the level of expression of G_{21} is at least 20, then the corresponding tissue is a tumor, otherwise it is normal. These algorithms seem as if they will eliminate what are called *redundant features* in the machine learning literature. To see what is meant by this, suppose for the sake of argument that two genes were always expressed to exactly the same extent. Then only one of the genes needs to be interrogated in a rule for classifying tissues, as the other does not provide any additional information. The feature selection algorithms that I have seen applied to microarray data eliminate (approximately) redundant features; but scientists in some cases want a complete list of genes involved in the disease process, including all members of clusters of genes with very similar patterns of expression across the tissues.

At present, colleagues and I are searching for practical methods to find more of the genes involved in a disease process using microarray data that aim to avoid both systematic sources of false negatives described above. It appears possible that consideration of theory might help to guide the design of algorithms of this type.

Thanks. I am very grateful to Wolfgang Maass and the other members of the Institut für Grundlagen der Informationsverarbeitung der Technischen Universität Graz for the very stimulating year I spent there in 1992-1993. I would also

like to thank Lance Miller for his comments on a draft of this note.

References

[1] T. R. Golub, D. K. Slonim, P. Tamayo, C. Huard, M. Gaasenbeek, J. P. Mesirov, H. Coller, M. Loh, J. R. Downing, M. A. Caligiuri, C. D. Bloomfield, and E. S. Lander. Molecular classification of cancer: class discovery and class prediction by gene expression monitoring. Science, 286:531-537, 1999.

[2] Jason Weston, Sayan Mukherjee, Olivier Chapelle, Massimiliano Pontil, Tomaso Poggio, and Vladimir Vapnik. Feature selection for SVMs. In NIPS, pages 668-674, 2000.

[3] E. Xing, M. Jordan, and R. Karp. Feature selection for high-dimensional genomic microarray data. Eighteenth International Conference on Machine Learning, 2001. ■

Prof. Dr. Phil Long, Ph.D. in computer science at the University of California in Santa Cruz, 1992-1993 Lise-Meitner-Postdoctoral fellow at the Institut für Grundlagen der Informationsverarbeitung der TU Graz, currently Associate Professor of the National University of Singapore and the Genome Institute of Singapore. Homepage: http://www.genomeinstitute.org

Computing with Spikes

Wolfgang Maass
Institut für Grundlagen der Informationsverarbeitung
Technische Universität Graz

A frightening thought for a computer scientist is that there might be completely different ways of designing computing machinery, that we may miss by focusing on incremental improvements of current designs. In fact, we *know* that there exist much better design strategies, since the human brain has information processing capabilities that are in many aspects superior to our current computers. Furthermore the brain does not require expensive programming, debugging or replacement of failed parts, and it consumes just 10-20 Watts of energy. Unfortunately, most information processing strategies of the brain are still a mystery. In spite of many positive reports in the media, even the most basic questions concerning the organization of the computational units of the brain and the way in which the brain implements learning and memory, have not yet been answered. They are waiting to be unraveled by concerted efforts of scientists from many disciplines. Computer science is one of the disciplines from which substantial contributions are expected, and in fact other countries have established already hundreds of research facilities in the new hybrid discipline *Computational Neuroscience*[1], which is dedicated to the investigation of computational principles in the brain. Computer scientists are contributing to these efforts through their experience in the evaluation of real and hypothetical systems that compute, as well as experience with robots and other machines that learn, move around, and explore their environment with their „senses" (vision, touch, hearing, etc.). In addition, an interesting theory called *computational complexity theory* has emerged in computer science during the last two decades. This theory provides analytical tools for judging whether a hypothetical model for the organization of computing and learning in the brain scales up from a „heuristic scale", where one draws wiring diagrams for a few dozens neurons and tests this model on simple computational tasks, to the real scale of the brain where more than 10^{10} neurons process in real-time a continuous stream of information from 10^8 sensory neurons, with instant (well, in some cases almost instant) access to a giant reservoir of stored information which is continuously updated. These experiences, tools, and results from computer science start to broaden the empirical basis for investigating terms from neuroscience and psychology such as learning, perception, and cognition. We are now in a position where we can test for example certain theories about learning by building a computer system based on this theory, and by evaluating how it performs. In fact, computer science provides even faster tools that allow us to test various theoretical ideas regarding cognition and learning through computer simulations on standardized benchmark tasks within a few hours or days. Obviously, having more opportunities for falsifying theories about the organization of information processing in the human brain is very desirable in the light of Popper's theory of science [15], and it creates new chances for approaching age-old questions about cognition and learning with more precise methods.[2]

Our institute contributes to research on neural computation through theoretical work based on complexity theory and computational learning theory, and through its interdisciplinary collaboration with Prof. Henry Markram's experimental neurobiology laboratory, which is moving this year from the Weizmann Institute in Israel to the new Brain Mind Institute at the Ecole Polytechnique Federale De Lausanne. Very important for our institute is also the ongoing exchange of ideas and methods with Prof. Rodney Douglas and the other experts for neurotechnology at the Institut für Neuroinformatik an der ETH Zürich.[3] Currently our joint work concentrates on three fundamental questions:

- What exactly is the computational function of neural microcircuits, which apparently represent the basic building blocks („chips") from which our brains are built?
- What are the principles by which learning and memory are organized in these neural microcircuits?
- What are the organizational principles by which millions of such neural microcircuits can communicate and collaborate in our brains?

Together we have discovered last year a new way of thinking about neural computation, see [11] and the articles by Henry Markram and Natschlaeger et al. in this issue, that differs

1 http://home.earthlink.net/~perlewitz/

2 Apart from the current work on computational models for neural systems that is sketched in this article, there also exists the area of *(artificial) neural networks*. This area had emerged several decades ago as a first attempt to capture aspects of neural computation in formal mathematical models. Neural networks have provided fruitful new ideas for machine learning and pattern recognition, but they are no longer viewed as an up-to-date way of modeling information processing in biological neural systems. Their computational units and organizational structure are too different, more precisely they reflect more ideas from computer science than from biology.

3 In contrast to our country, Switzerland is expecting major scientific and technological benefits from research in these areas – it has established during the past 10 years several new institutes in the areas Computational Neuroscience and Neuroinformatics, with well over a hundred researchers.

radically both from traditional ways of designing computers, and from preceding models for neural computation (which obviously are strongly inspired by current computer designs). This new approach takes into account that neural circuits acquire through their numerous feedback connections („recurrent connectivity“) and the rich temporal dynamics of their components a computational life of their own, which cannot be understood by just looking at their components, neurons and synapses. Since this setup is so different from computational systems that can be analyzed with models related to Turing machines, we have developed a new conceptual framework. Based on this approach we can now for the first time carry out complex real-time information processing tasks on quite realistic computer models of neural microcircuits (see [11], [5]). In order to understand the ideas behind this work, one first needs to get a rough idea about neurons and synapses, the components of neural microcircuits. Therefore the remainder of this article is devoted to a quick introduction to *wetware*.

If you pour water over your PC, the PC will stop working. This is because very late in the history of computing – which started about 500 million years ago[4] in and near to the sea – the PC and other devices for information processing were developed that require a dry environment. We still carry an echo of this history of computing in our heads: the neurons in our brain are embedded into an artificial sea-environment, the salty aqueous extracellular fluid which surrounds the neurons in our brain. The close relationship between the wetware in our brain, and the wetware in evolutionary much older organisms that still live in the sea, is actually quite helpful for research. Neurons in the squid are 100 to 1000 times larger than the neurons in our brain, and therefore easier to study. Nevertheless the mathematical equations that Hodgkin and Huxley derived to model the dynamics of the neuron that controls the escape reflex of the squid (for which they received the Nobel prize in 1963), also apply to the neurons in the human brain.
One of the technical problems that nature had to solve for enabling computation in wetware was how to communicate intermediate results from the computation of one neuron to other neurons, or to output-devices such as muscles. In a PC one sends streams of bits over copper wires.

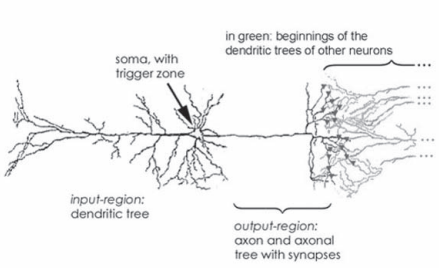


Fig:1: *Simplified drawing of a neuron, with input region, the cell body or soma (the trigger zone lies at its right end of the soma, just where the axon begins), and output region. Synapses are indicated by blue triangles.*

But copper wires were not available a few hundred million years ago, and they also do not work so well in a sea-environment. The solution that nature found was the so-called action potential or *spike*. The spike plays in a brain a similar role as a bit in a digital computer: it is the common unit of information in wetware. A spike is a sudden voltage increase (see Figure 2) for about 1 ms (1 ms = 1/1000 second) that is created at the cell body (soma) of a neuron, more precisely at its *trigger zone*, and propagated along a lengthy fiber (called axon) that extends from the cell body. This axon corresponds to an insulated copper wire in hardware. It contains active zones (the nodes of Ranvier), where the shape of the propagated spikes is restored. The gray matter of the human brain contains a large amount of such axons: about 4 km in every cubic millimeter. Axons have numerous branching points (see the axonal tree on the right hand side of Figure 1), where most spikes are duplicated, so that they can enter each branch of the axonal tree. In this way a spike from a single neuron can be transmitted to a few thousand other neurons.

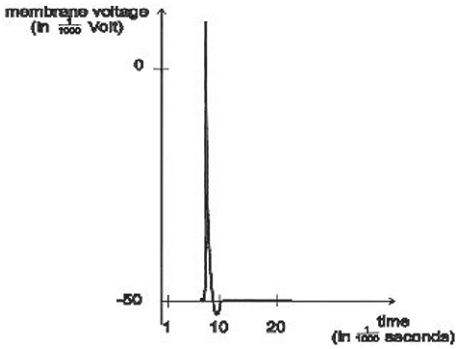


Fig:2: *Time cause of an action potential at the soma of a neuron.*

But in order to move from one neuron to another, the spike has to pass a rather complicated information transmission device, a so-called *synapse* (marked by a blue triangle in Figure 1, and shown in more detail in Figure 3). When a spike enters a synapse, it is likely to trigger a complex chain of events that are indicated in Figure 3[5]: a small vesicle filled with special molecules („neurotransmitter“) is fused with the cell membrane of the presynaptic terminal, thereby releasing its content, the neurotransmitter, into the extracellular fluid. Whenever a neurotransmitter molecule reaches a particular molecular arrangement (a „receptor“) in the cell membrane of the next neuron, it will

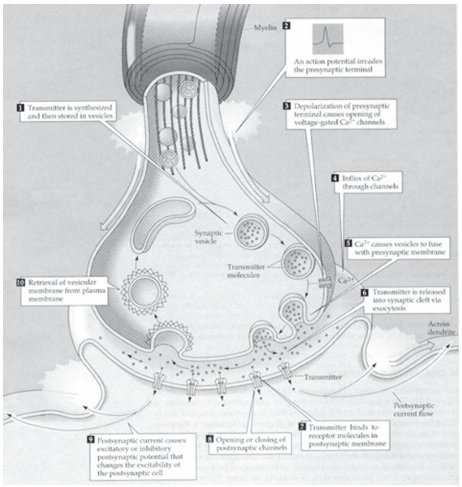


Fig.3: *The spike enters the presynaptic terminal, which is an endpoint of the axonal tree of the preceding neuron, shown on the top. It may cause a vesicle filled with neurotransmitter to fuse with the cell membrane, and to release its neurotransmitter molecules into the small gap (synaptic cleft) to the cell membrane of the next neuron (called postsynaptic neuron in this context), which is shown at the bottom. If the neurotransmitter reaches a receptor of the postsynaptic neuron, a channel will be opened that lets charged particles pass into the postsynaptic neuron. Empty vesicles are recycled by the presynaptic terminal.*

open a channel in that cell membrane through which charged particles (ions) can enter the next cell. This causes an increase or decrease (depending on the type of channel that is opened and the types of ions that this channel lets through) of the membrane voltage by a few millivolt (1 millivolt = 1/1000 volt). One calls these potential changes EPSPs (excitatory postsynaptic potentials) if they increase the

4 According to current scientific knowledge about 500 million years ago, during heavy evolutionary pressure on all living organisms caused by drastic climatic changes, the first organisms with a nervous system emerged. But one could also argue that the history of computing started somewhat earlier, even before there existed any nervous systems: 3 to 4 billion years ago when nature discovered information processing and storage via RNA.

5 See http://www.wwnorton.com/gleitman/ch2/tutorials/2tut5.htm for an online animation.

membrane voltage, and IPSPs (inhibitory postsynaptic potentials) if they decrease the membrane potential. In contrast to the spikes, which all look alike, the size and shape of these postsynaptic potentials depends very much on the particular synapse that causes it. In fact it will also depend on the current „mood“ and the recent „experiences“ of this synapse, since the postsynaptic potentials have different sizes, depending on the pattern of spikes that have reached the synapse in the past, on the interaction of these spikes with the firing activity of the postsynaptic neuron, and also on other signals that reach the synapse in the form of various molecules (e.g. neurohormones) through the extracellular fluid. Hence a synapse is not a static signal transformer like a modem, but rather an intelligent preprocessor, that modulates the currently transmitted information in the light of experiences stretching from the recent past way back into the history of the organism. The human brain contains about 10^{15} of these synapses.

Sometimes people wonder whether it is possible to replace wetware by hardware, to replace for example parts of a brain by silicon chips. This is not so easy because wetware does not consist of fixed computational components, like a silicon chip, that perform the same operation in the same way on every day of its working life. Instead, the channels and receptors of neurons and

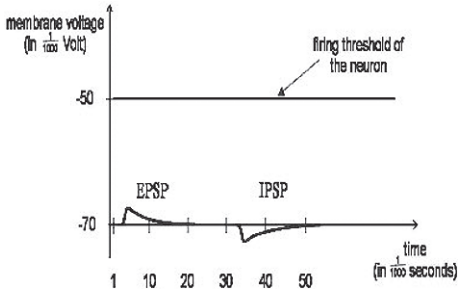


Fig.4: *Postsynaptic potentials are either excitatory (EPSP) or inhibitory (IPSP). The membrane voltage is a sum of many such postsynaptic potentials. As soon as this sum reaches the firing threshold, the neuron fires.*

synapses move around, disappear, and are replaced by new and possibly different receptors and channels that are continuously reproduced by a living cell in dependence of the individual „experience“ of that cell (such as the firing patterns of the pre- and postsynaptic neuron, and the cocktail of biochemical substances that reach the cell through the extracellular fluid). This implies that next year a synapse in your brain is likely to perform its operations quite differently from today, whereas a silicon clone of your brain would be stuck with the „old“ synapses from this year. Thus we would need new types of *adaptive* hardware to replace the function of neural circuits in wetware.

The postsynaptic potentials created by the roughly 10.000 synapses converging on a single neuron are transmitted by a tree of input wires („dendritic tree“, see Figure 1) to the *trigger zone* at the cell body of a neuron. Whenever the sum of these hundreds and thousands of continuously arriving voltage changes reaches the firing threshold at the trigger zone, the neuron will „fire“ (a chain reaction orchestrated through the rapid opening of channels in the cell membrane that allow positively charged sodium ions to enter the neuron, thereby increasing the membrane voltage, which causes further channels to open) and send out a spike through its axon.[6] So we are back at our starting point, the spike. Altogether one might argue that the all-or-nothing nature of a spike (since there are no half-spikes etc.) points to a *digital* type of computation in neural systems. But on the other hand in the absence of a global clock or synchronization device the time when a spike is sent is an important *analog* signal. Furthermore we have seen that numerous analog processes (especially at the synapses) modulate

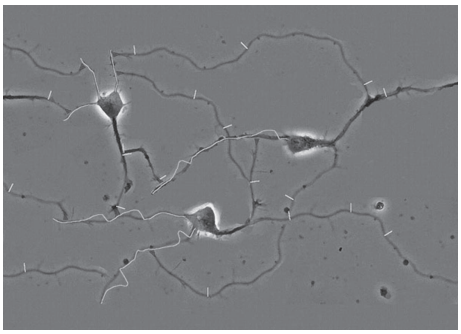


Fig.5: *A simulated network of 3 neurons. Postsynaptic potentials in the input regions of the neurons (dendritic tree) are indicated by green curves. Spikes are indicated by white bars on the axons, and synapses by blue triangles. In the online available computer installation you can create your own input spike train, and watch the response of the network. You can also change the strength of the synapses, a process that may correspond to learning in your brain. See [7], (http://www.igi.TUGraz.at/maass/118/118.html) for more detailed information.*

the effects that a spike has on other neurons, and thereby the time when these other neurons will send out their next spike. Thus neural computation turns out to be a hybrid mixture of analog and digital computing.

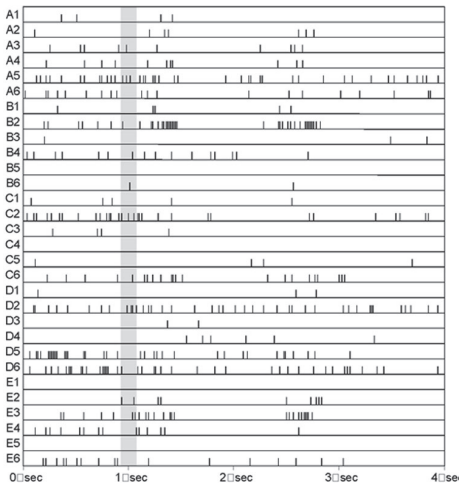


Fig.6: *Recording of spike trains from 30 neurons in the visual cortex of a monkey over 4 seconds. The 30 neurons were labeled A1 – E6 (the labels are given on the left of the figure). The spike train emitted by each of the neurons is recorded in a separate row. Each point in time when a neuron fires and thereby emits a spike is marked by a small vertical bar. Hence one could read this figure like a music score.*
The time needed for a typical fast computation in the human brain is marked by a vertical gray bar; these are 150ms. Within this time the human brain can solve quite complex information processing problems, like for example the recognition of a face. Currently our computers would need a substantially longer computation time for such tasks.

The question is now how a *network of neurons* can compute with spikes. Figure 5 presents an illustration of a tiny network consisting of just 3 neurons, which communicate via sequences of spikes (usually referred to as *spike trains*). It is taken from an animated computer installation which is online available[7]. It allows you to create your own spike train, and watch how the network responds to it. You can also change the strength of the synapses, and thereby simulate (in an extremely simplified manner) processes that take place when the neural system „learns“. But we

6 See http://www.wwnorton.com/gleitman/ch2/tutorials/2tut2.htm for an online animation.

7 See http://www.igi.TUGraz.at/demos/index.html. This computer installation was programmed by Thomas Natschlaeger and Harald Burgsteiner, with support from the Steiermaerkische Landesregierung. Detailed explanations and instructions are online available from http://www.igi.TUGraz.at/maass/118/118.html, see [7]. Further background information is online available from [14], [6], [8].

still do not know how to transmit information via spikes, hence let us look at the protocol of a real computation in wetware.

In Figure 6 the spike trains emitted by 30 (randomly selected) neurons in the visual area of a monkey brain are shown for a period of 4 seconds. All information of your senses, all your ideas and thoughts are coded in a similar fashion by spike trains. If you would for example make a protocol of all the visual information which reaches your brain within 4 seconds, you would arrive at a similar figure, but with 1.000.000 rows instead of 30, because the visual information is transmitted from the retina of your eye to your brain by the axons of about 1.000.000 neurons.

Researchers used to think that the only computationally relevant signal in the output of a neuron was the frequency of its firing. But you may notice in Figure 6 that the frequency of firing of a neuron tends to change rapidly, and that the temporal distances between the spikes are so irregular that you have a hard time estimating the average frequency of firing of a neuron by looking at just 2 or 3 spikes from that neuron. On the other hand the human brain can compute quite fast, in about 150 ms, with just 2 or 3 spikes per neuron. Hence other features of spike trains must be used by the brain for transmitting information. Recent experimental studies (see for example [17], [3], [16]) show that in fact the full spatial and temporal pattern of spikes emitted by neurons is relevant for the message which they are sending to other neurons. Hence it would be more appropriate to compare the output of a collection of neurons with a piece of music played by an orchestra. To recognize such piece of music it does not suffice to know how often each note is played by each musician. Instead we have to know how the notes of the musicians are embedded into the melody and into the pattern of notes played by other musicians. One assumes now that in a similar manner many groups of neurons in the brain code their information through the pattern in which each neuron fires relative to the other neurons in the group. Hence, one may argue that music is a code that is much closer related to the codes used by the human brain than the bit-stream code used by a PC.

The investigation of theoretical and practical possibilities to compute with such spatio-temporal patterns of pulses has lead to the creation of a new generation of artificial neural networks, so-called *pulsbased* neural networks (see [9] and [2] for surveys and recent research results). Such networks are appearing now also in the form of novel electronic hardware [12], [1], [13]. An interesting feature of these pulsbased neural networks is that they do not require a global synchronisation (like a PC, or a traditional artificial neural network). Therefore they can save a lot of energy[8], since no clock signal has to be transmitted at every moment to all components of the network, even if there is currently nothing to compute. Furthermore neurons can use *time* as a new dimension for *coding information*, for example by firing simultaneously or in a specific temporal pattern. One big open problem is the *organization of computation* in such systems, since the operating system of wetware is still unknown, even for the squid. Hence our current research, jointly with the neurobiologist Prof. Henry Markram, concentrates on the organization of computations in neural microcircuits, the lowest level of circuit architecture in the brain. Our approach is based on a novel theoretical model, the liquid state machine, which strongly differs from Turing machines and other traditional computational models. More information on this recent development can be found in the subsequent two articles of this volume, as well as in the research reports [11], [10], [5].

Acknowledgement

I would like to thank Margot Göttsberger and Dr. Thomas Natschläger for helpful comments on an earlier draft of this paper.

References

[1] Deiss, S. R., Douglas, R. J., and Whatley, A. M. (1999). *A pulse-coded communications infrastructure for neuromorphic systems*. In Maass, W., and Bishop, C., editors, Pulsed Neural Networks. MIT-Press, Cambridge.

[2] Grossberg, S., Maass, W., and Markram, H., editors (2001). Spiking Neurons in Neuroscience and Technology. *Special Issue of Neural Networks*, vol. 14 (6-7).

[3] Koch, C. (1999). *Biophysics of Computation: Information Processing in Single Neurons*. Oxford University Press (Oxford).

[4] Krüger, J., and Aiple, F. (1988). *Multielectrode investigation of monkey striate cortex: spike train correlations in the infragranular layers*. Neurophysiology, 60:798-828.

[5] Legenstein, R., Maass, W., and Markram, H. (2002). *Input Prediction and Autonomous Movement Analysis in Recurrent Circuits of Spiking Neurons*, submitted for publication.

[6] Maass, W. (2000a). *Das menschliche Gehirn – nur ein Rechner?*. In Burkard, R. E., Maass, W., and P. Weibel, editors, Zur Kunst des Formalen Denkens, pages 209-233. Passagen Verlag (Wien), 2000. See http://www.igi.tugraz.at/maass/KFD/

[7] Maass, W. (2000b). *Spike trains – im Rhythmus neuronaler Zellen*. In Kriesche, R., and Konrad, H., editors, Katalog der steirischen Landesausstellung gr2000az, pages 36-42. Springer Verlag. See # 118 on http://www.igi.tugraz.at/maass/publications.html

[8] Maass, W. (2002). *Paradigms for computing with spiking neurons*. In Leo van Hemmen, editor, Models of Neural Networks, volume 4. Springer (Berlin), to appear. See # 110 on http://www.igi.tugraz.at/maass/publications.html

[9] Maass, W., and Bishop, C., editors (1999). *Pulsed Neural Networks*. MIT-Press (Cambridge, MA). Paperback (2001). See http://www.igi.tugraz.at/maass/PNN.html

[10] Maass, W., and Markram, H. (2002) *On the Computational Power of Recurrent Circuits of Spiking Neurons*, submitted for publication.

[11] Maass, W., Natschlaeger, T., and Markram, H. (2001). *Real-time computing without stable states: a new framework for neural computation based on perturbations*, submitted for publication.

[12] Mead, C. (1989). *Analog VLSI and Neural Systems*. Addison-Wesley (Reading).

[13] Murray, A. F. (1999). *Pulse-based computation in VLSI neural networks*. In Maass, W., and Bishop, C., editors, Pulsed Neural Networks. MIT-Press (Cambridge, MA).

[14] Natschlaeger, T. (1996). *Die dritte Generation von Modellen für neuronale Netzwerke Netzwerke von Spiking Neuronen*. In: Jenseits von Kunst, Peter Weibel editor. Passagen Verlag. See http://www.igi.tugraz.at/tnatschl/

[15] Popper, K. (1959). *The Logic of Scientific Discovery*. Hutchinson (London).

[16] Recce, M. (1999). *Encoding information in neuronal activity*. In Maass, W., and Bishop, C., editors, Pulsed Neural

8 Wetware consumes much less energy than any hardware that is currently available. Our brain, which has about as many computational units as a very large supercomputer, consumes just 10 to 20 Watt.

Networks. MIT-Press (Cambridge, MA).

[17] Rieke, F., Warland, D., Bialek, W., and de Ruyter van Steveninck, R. (1997). *SPIKES: Exploring the Neural Code*. MIT-Press (Cambridge, MA). ■

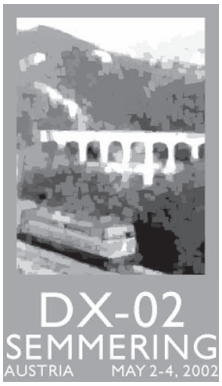
Prof. Dr. Wolfgang Maass, computer scientist and mathematician, Ph.D. under Prof. K. Schütte (Mathematical Logic) at the University of Munich, 1986-1991 Professor at the University of Illinois (Chicago), since 1991 Professor at the TU Graz, since 1992 Head of the Institut für Grundlagen der Informationsverarbeitung der TU Graz. Homepage: http://www.igi.tugraz.at/maass

Vorschau Ausgabe 02/2002

Thema: „Überwachung und Diagnose“
Editor: Ao. Univ.-Prof. DI Dr. Bernhard Rinner
Institut für Technische Informatik, TU Graz

Die automatisierte Überwachung und Diagnose von diversen Systemen nimmt ständig an Bedeutung zu. Wesentliche Gründe dafür sind die wachsende Komplexität der zu überwachenden Systeme, die erhöhten Anforderungen bezüglich der Ausfallssicherheit aber auch der Kostendruck der Wirtschaft und die damit verbundene Reduktion von Personal für Überwachung und Instandhaltung. Telematik widmet sich in der nächsten Ausgabe diesem Thema und beschreibt aktuelle Ansätze und Anwendungen aus diesem Bereich.

Einsendeschluss ist der **15. Mai 2002**.



13th International Workshop on Principles of Diagnosis (DX-02)

2-4 May, 2002
Semmering, Austria

This international workshop series, originating within the Artificial Intelligence community, focuses on theories, principles and computational techniques for diagnosis, testing, reconfiguration and repair of complex systems. Complex systems can be large hardware systems, continuous, discrete, or hybrid systems, but also programs and a combination of all. The workshop also focuses on transfer of these theories, principles and techniques to industrial applications of diagnostic problem solving. This lively annual forum fosters interaction and cooperation among researchers with diverse interests and approaches to diagnosis in Artificial Intelligence, such as model-based and qualitative reasoning, as well as in related areas, such as FDI, control, and software debugging. The workshop has traditionally adopted a single-track program, and limited the number of participants to support technical exchange and debate. This year we are especially interested in demonstrations of diagnosis applications and prototypes of diagnosis engines together with runtime performance analysis and comparisons to other implementations.

We solicit papers in a variety of areas related to diagnostic problem solving, including but not limited to:

- Formal theories of and computational methods for diagnosis, monitoring, testing, repair, reconfiguration and related topics.
- Modeling: symbolic, numeric, discrete, continuous, hybrid discrete/continuous, probabilistic, functional, behavioral, and qualitative modeling, as well as abstractions and approximations.
- Computational issues: controlling combinatorial explosion, focusing strategies, limiting computation for complex systems, use of structural knowledge, use of hierarchical knowledge, abstraction and approximation techniques.
- The diagnosis process: repair strategies, sensor placement, test selection, resource-bounded reasoning, real-time diagnosis, on-board autonomous operation, active testing, experiment design, predictive diagnosis, contingency planning.
- Connections between diagnosis and other areas: FDI techniques, control theory, design, machine learning, nonmonotonic reasoning, planning, execution, Bayesian reasoning, Markov modeling, real time languages, software V&V, debugging, synthesis, hardware testing, philosophical issues on diagnosis and modeling.
- Principled applications and technology transfer: real-world applications and integrated systems in a wide range of fields including medical, chemical, mechanical, electrical, electro-mechanical and electronics systems. We especially welcome insights on whether and why a specific technique succeeded (or failed) in a realworld context.

For those who wish to attend the Workshop without submitting a paper, please email a short abstract describing your research interests to dx2002@dbai.tuwien.ac.at by February 7, 2002. Invitations will be mailed out by March 15, 2002. To promote active discussion at the workshop, attendance will be by invitation only.

Structural and Functional Principles of Neocortical Microcircuits

Henry Markram
Brain Mind Institute
Ecole Polytechnique Federale De Lausanne

The neocortex subserves perception, attention, memory, and a spectrum of other higher cognitive functions. At the heart of these functions lies an intricate microcircuit of neurons. There are several aspects of this microcircuit design, which suggests that the nervous system solves computational problems in a fundamentally different way from conventional digital computers.

First, a seemingly stereotypical microcircuit of neurons is used for all the tasks required of the neocortex. While there are specializations in the microcircuit structure in different parts of the neocortex and in different species of animals, it seems that these differences are more related to adaptations required for receiving and sending specific forms of information rather than to adapt the microcircuit to process information differently – the principal means of computation stays the same. This suggests that in the neocortex, the same microcircuit can perform a vast, perhaps even an unlimited spectrum of functions and indicates that the elemental „neocortical microcircuit chip" is an omnipotent chip.

Second, in the same region of the neocortex, researchers have shown multiple functions overlaid simultaneously on the same microcircuit, indicating that this chip not only possesses the flexibility to perform a vast number of different functions, but it can also carry out these tasks simultaneously. This form of unrestricted parallel computation seems to be a fundamental component of neuronal processing since it allows simultaneous integration of multiple features of the world with their relevant associations.

Third, while the neocortex is divided into millions of tiny functional chips - each chip is a column about half mm in diameter and 1-2 mm high, there are no fixed anatomical boundaries between „chips". In other words, the neocortex is a continuous sheet of interconnected neurons and these chips are dynamically formed according to the activity requirements of the neocortex such that any location on the neocortex could be a center point of a chip. This holographic-like principle for microcircuit structure arises from the way that the neurons connect to each other and the stabilization of the location of functional chips arises from that way that information is mapped into and out of the neocortex to correspond with the sensory and motor systems of the body.

Forth, a functional microcircuit chip is made up of an extremely dense group of neurons (tens of thousands of neurons within the size of a pinhead, ~0.2-0.4 mm^2). The key principles that underlie the formation of this chip are „diversify the components" and „map each neuron precisely onto each other neuron". The chip is not only made up of an incredibly large variety of neuron types but also synapse types that are used to interconnect the neurons meaning that each connection serves as a unique translator of information between any two neurons. This is a remarkable design principle because each neuron can contact several hundred other neurons, but each target neuron will interpret a single sent by any one neuron in a different manner. We refer to this as differential signaling.

Fifth, the connections between the neurons do not transmit information in a constant or static manner – they dynamically change the strength of transmission on the millisecond timescale, allowing incoming information to configure the functional architecture.

Sixth, functionally the chip seems to be engineered to overlay as many time scales of information processing as possible, essentially a continuum, with time constants of processing ranging from a few microseconds to years. This poses a profound challenge for computational models that dare to include some of the complexity of the microcircuit, because it is almost impossible for the activity to „equilibrate" with even a constant sensory input, let alone a rapidly and continuously changing real-world environment. In other words, the activity space of such a microcircuit is closer to that of a dynamical system where the activity moves along a continuous trajectory of states which may not necessarily ever repeat itself.

Seventh, the dynamic connections between neurons are organized with extreme precision to match the functions of the different types of neurons within the chip, giving rise to a functional correlate of the structural design.

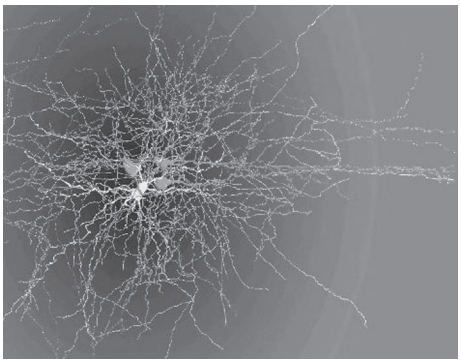
Eighth, the chip possesses a remarkable ability to adapt to new environments, which is the central feature that has made mammals a dangerously successful species, and that allows humans to rapidly adapt to new environments. The principles of adaptation seem to involve the orchestration of *three principles*: The *first* is an unsupervised learning of synapses that allows the chip to dynamically reconfigure itself and optimize the processing of information within the chip. We think that the synapses are optimized to maximize entropy in the neuron and in the chip. In a sense, this form of learning is not related to remembering information per se, but to the chip learning about itself and optimizing itself. The *second* component is supervised learning where a spectrum of neurochemicals are used to teach the chip about global directives of the whole animal. This form of learning is extremely complex and involves a wide spectrum of gating mechanisms where different synapses are gated in different ways. Such complex gating may be required to systematically fragment a broad goal into a pyramid of sub goals and instruct synapses about the outcome of the behavior. The *third* component allows for different chips and brain areas to learn about each other, calibrating their information representations in order to produce a meaningful and orchestrated output from the animal.

These eight points describe just some of the major structural and functional features of computation in the neocortical microcircuit and illustrate that neural computation is fundamentally different from conventional digital computing. To explore new forms of computing I started collaborating with Prof. Wolfgang Maass from the Institut für Grundlagen der Informationsverarbeitung der Technischen Universität Graz. Prof. Maass's precise approaches, mathematical tools, experience in other forms of neural network computing as well as in conventional forms of computation provide an invaluable approach to begin addressing these biological challenges and ask – what are the key principles of neural computation? Such a collaboration could bring interesting new insights into neural computing, to new forms of neuromorphic engineering and perhaps even revolutionize conventional computing approaches. Indeed, we came up with a powerful new framework that we now refer to as „Liquid Computing", which may explain how these neocortical microcircuits are able to solve many of the key problems these microcircuits face.

In principle, an artificial microcircuit must be able to solve *four fundamental problems* before it can approach computation in a real neural system. *First*, it must be able to deal with a continuous inflow of information. It is essentially impossible to stop the stream of 1000's of bits of information per second and give the system time to process it. The artificial device must therefore have an almost unrestricted buffer capacity and be able to process information at the same time that the information is being buffered. *Second*, the artificial device must be able to respond at any moment in time – real-time computation – and not have to wait for a processing step to complete before being able to generate an answer. *Third*, the device must be capable of temporal integration. Spatial integration is a relatively easier problem, but temporal integration requires combining information over any combination of time points back in the past. In a sense, all past information must be available instantly for readout to fuse time points and create the temporal relational aspect of objects. *Forth*, the artificial device must be able to carry out an almost unrestricted number of tasks in parallel. The usual strategy is to use synchrony across different phases of oscillations to share the activity among tasks, but we believe that all these tasks are performed by the same activity – a form of multidimensional representation.

Liquid computing is computation based on perturbations of the system rather than on any defined states. The information is represented in a continuous trajectory of states. We found that it is not too difficult to extract information and generate stable responses from such a dynamical system. We have shown that the current state of perturbations of such a high dimensional dynamical system contains a vast amount of information about the past and is readily accessible by readout neurons. These readout neurons can assign their own notion of equivalence for different states of the system, dispensing with the need of the system to ever repeat the same state in order to generate a stable perception or output. Liquid computing therefore explains how a recurrent microcircuit can act as an unrestricted buffer, a source of real-time information, the ultimate temporal integrator and a system that enables unrestricted parallel computing. From the biological perspective the framework of liquid computing also allows us new approaches to explore the intriguing structural and functional principles of the neocortical microcircuit chip.

Our lab is currently moving from the Weizmann Institute in Israel to the new Brain Mind Institute at the EPFL/ETH Lausanne where we aim to begin a comprehensive virtual reconstruction of the neocortical microcircuitry from the genetic to the circuit level and where we aim to devote large resources to exploring the limits and applications of liquid computing. ■



The figure shows three excitatory neurons (blue) and a single inhibitory neuron (white). The horizontal expanse of these neurons is around 0.3 mm which is an approximate diameter of a functional neocortical microcircuit. The column is 1-2 mm high and contains up to 70,000 neurons.

Prof. Dr. Henry Markram, graduate student of Prof. R. Douglas at the University of Cape Town (South Africa), Ph.D. under Prof. M. Segal at the Weizmann Institute for Science in Rehovot (Israel), since 1998 Professor in the Department of Neurobiology at the Weizmann Institute for Science, since 2002 Director of the new Brain Mind Institute at the Ecole Polytechnique Federale de Lausanne (EPFL).
Homepage: http://www.weizmann.ac.il/neurobiology/labs/markram/markram.html

The „Liquid Computer“: A Novel Strategy for Real-Time Computing on Time Series

Thomas Natschläger[*], *Wolfgang Maass*[*], *Henry Markram*[+]
[*] *Institut für Grundlagen der Informationsverarbeitung, Technische Universität Graz*
[+] *Brain Mind Institute, Ecole Polytechnique Federale De Lausanne*

Abstract

We will discuss in this survey article a new framework for analysing computations on time series and in particular on spike trains, introduced in [1]. In contrast to common computational models this new framework does not require that information can be stored in some stable states of a computational system. It has recently been shown that such models where all events are transient can be successfully applied to analyse computations in neural systems and (independently) that the basic ideas can also be used to solve engineering tasks such as the design of nonlinear controllers.

Using an illustrative example we will develop the main ideas of the proposed model. This illustrative example is generalized and cast into a rigorous mathematical model: the Liquid State Machine. A mathematical analysis shows that there are in principle no computational limitations of liquid state machines in the domain of time series computing. Finally we discuss several successful applications of the framework in the area of computational neuroscience and in the field of artificial neural networks.

Introduction

The analysis of computation in neural systems has often concentrated on the processing of static stimuli. However, numerous ecologically relevant signals have a rich temporal structure, and neural circuits must process these signals in real time. In many signal processing tasks, such as audition, almost all of the information is embedded in the temporal structure. In the visual domain, movement represents one of the fundamental features extracted by the nervous system. Hence it is not surprising that in the last few years there has been increasing interest in the dynamic aspects of neural processing. Processing of real-world time-varying stimuli in real-time is a difficult problem, and represents an unsolved challenge for computational models of neural functions. Simultaneously in computer science several areas such as for example computer vision, robotics, and machine learning have also increased their efforts to deal with dynamic real-world inputs.

Computational models that are commonly used as conceptual basis for the investigation of computations in biological neural systems are Turing machines, finite state machines (automata), and attractor neural networks. These models have in common that they can store bits in a suitable number of stable states, for example attractors (or limit cycles) of an attractor neural network. This capability appears to be less ubiquitous in biological neural systems, since its components exhibit a strong inherent dynamics on several time scales, and in many instances the only stable state is the „dead“ state. This observation has motivated us to investigate the question whether there are alternative computational models that do not have to rely on states that remain stable, but rather can be implemented in an environment where all states are transient and are able to process time-varying stimuli in real-time.

In order to approach this question with a fresh mind, one might for example think of carrying out computations in a liquid medium, such as a cup of coffee. As motivated above, the type of computation we want to consider are computations on time series, i.e. computations whose inputs $u(\cdot)$ are functions of time, and whose outputs are again certain functions $v(\cdot)$ of time. Such functions that map input time series $u(\cdot)$ on output time series $v(\cdot)$ are usually called operators in mathematics, but are commonly referred to as filters in engineering and neuroscience. We use the term filter in the following.

In the example of computing with a liquid one could for instance view as input time series the sequence of perturbations (for example when a spoon hits the surface of the coffee or sugar cubes that drop into the cup) that continually affect the liquid. The output could be an online (at any time t) classification of the sources of all perturbations that have recently occurred, or a prediction of the next perturbations that are to be expected. The output can for example be computed by a laptop PC from an image of the surface of the liquid which is recorded with a digital camera. We call such a setup the „liquid computer“ (see Figure 1).

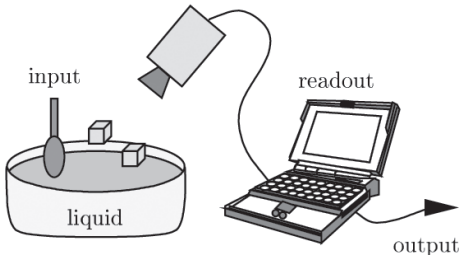


Fig.1: *The „liquid computer“. The „liquid“ (e.g. cup of coffee) gets as input a sequence of perturbations (e.g. spoon hits or sugar cubes dropped). These perturbation are transformed in real-time into „liquid states“ (e.g. an image of the surface of the liquid). A memory-less readout (in the sense that it has no access to past states) transforms this liquid states into the desired output time series.*

Note that the idea of the „liquid computer“ is not restricted to the particular choice of the liquid (cup of coffee) and the readout (camera plus PC) given in this illustrative example; this is discussed in more detail in the next Section.

An image of the surface of the liquid taken at time t can be considered as the current state of the liquid or simple the liquid state $x(t)$.[1] It is obvious that computations in the „liquid computer“ can not relay on stable states since the only stable state of the liquid is the „dead

state“ (see Fig. 2), and all perturbations of the liquid trigger transient events.

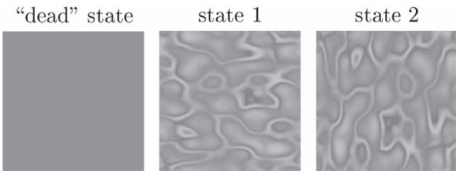


Fig.2: *Images of the surface of the liquid are considered as the states of the liquid. State 1 and 2 are generated by two different input time series, i.e. series of perturbations (spoon hits and sugar cubes dropped).*

We will argue that for all interesting target filters which one wants to implement with a „liquid computer“ it is sufficient to compute the output via a suitable readout mechanism at any time t only from the current state $x(t)$ of the liquid. This will enable the „liquid computer“ to produce its output in real-time: it does not have to wait explicitly until it has gathered enough information to compute the output. In the example of the „liquid computer“ shown in Fig. 1 this means: to compute the output at time t the PC only needs to access the image which was taken at time t but no other images taken before time t, i.e. there is no need for the PC to store images, or features of earlier images. In other words: we propose the hypothesis that it is sufficient to apply a memory-less device - in the sense that it has no access to states prior to time t - as readout to compute the desired output from the current state $x(t)$ of the liquid.

How can a „liquid computer“ implement a desired target filter for which it is definitely necessary to have access to inputs at times $t' < t$ to compute the output at time t (e.g. output at time t the number of sugar cubes dropped into the liquid within the last 2 seconds)? The basic idea is that the current state $x(t)$ at time t of the liquid has to hold all the relevant information about the input. Informally this requires that any two different input time series which should produce different output time series put the liquid into two (significant) different states (see Fig. 2). If the liquid has this property it is at least in principle possible to find a suitable memory-less readout (in the sense that it has no access to states prior to time t) to compute the desired outputs in a real-time fashion.[2]

From this point of view one can interpret the readout as a device which retrieves the desired information about the input from the current state of the liquid. Obviously this task of the readout can be accomplished more easily if the states of the liquid contain in a „clearly visible“ form the information about the input which the readout is supposed to pick out. Which features of the input are „clearly visible“ in the states of the liquid depend on the internal structure of the liquid, for example on the type and range of interaction between the individual elements the liquid is composed of. In particular the internal structure of a liquid determines over which time and spatial scales the inputs are integrated (mixed) and produce the states of the liquid. Hence the internal structure of the liquid determines how useful (for the readout) the states of the liquid are. Unfortunately the internal structure of real liquids like coffee are such that it has rather small time constants for relaxation, and perturbations are propagated only through the very local interaction between molecules. This makes a cup of coffee less suitable as computational device.

However, neural circuits could constitute ideal „liquids“ because of the distributed interactions between its elements (neurons) and the large variety of time scales present in this systems. These characteristic features potentially allow neural systems to function as an optimal integrator of all kinds of sensory input. Optimal in the sense that the state of the neural system serves as a universal source of information about present and past stimuli which can be used by a simple readout mechanism (e.g. a single neuron) to compute any desired output. In fact it was found in [1] by computer simulations that models of small neural circuits can indeed be used as a „liquid“ and that readout maps can be trained such that a given task is accomplished. Independently the basic ideas of the „liquid computer“ have been investigated in [2] from an engineering point of view. In that work artificial recurrent neural networks (see e.g. [3]) have been used as a „liquid“ and simple linear readout functions have been trained to fulfill several different tasks.

In section 2 we will make these informal ideas about the „liquid computer“ more precise, and discuss the general (and more formal) model introduced in [1] for analysing computations on time series: the liquid state machine (LSM). We will formulate two simple conditions, the separation property and the approximation property, which - if met - endow any LSM with in principle universal computational power in the time series domain. This analysis shows that devices where the effects of the most common perturbations are transient, can still be computationally powerful. In section 3 we will discuss several successful applications of the LSM approach.

The Liquid State Machine

A formal model of a „liquid computer“

The liquid state machine (LSM) introduced in [1] is a mathematical model of the „liquid computer“. Its basic structure is depicted in Figure 3.

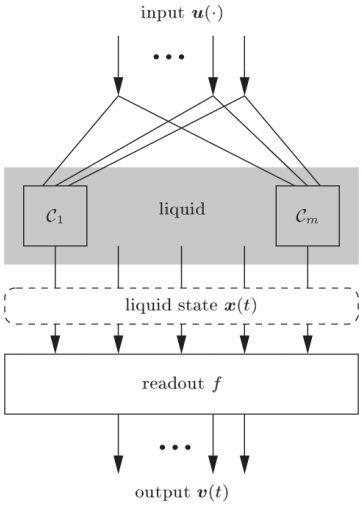


Fig.3: *A mathematical model of the „liquid computer“: the liquid state machine. The liquid transforms the input into liquid states x(t), which are mapped by the memory-less readout function f to the output v(t) = f (x(t)).*

A LSM consists of some liquid which transforms the input time series $u(\cdot)$ into „liquid states“ $x(t)$. A memory-less readout function f maps the „liquid state“ $x(t)$ at time t into the output $v(t) = f(x(t))$. Note that there are no assumptions about the concrete implementation of the liquid and the readout function.

It is simply assumed that the liquid integrates inputs $u(t')$ for $t' < t$ into liquid states $x(t)$ for all times t. From a dynamical systems point of view the liquid is a non-autonomous dynamical system (see [4]) and the time varying function

1 Note that such an image of the surface of the liquid does not describe the full state of the liquid if considered as a dynamical system. The full state of a cup of coffee considered as dynamical system would contain the positions and velocities of all particles within the cup.

2 Of course a nowadays PC would have enough memory to record a whole stream of images during the last 2 seconds. However, if all relevant information to compute the output $v(t)$ attime t is already contained in the state $x(t)$ it is a) not necessary to store anything about the past and b) wasteful to discard this information since it would probably take more time to compute the output $v(t)$ from several images (about 50 images for 2 seconds of history). Furthermore point b) would imply that the output of the readout can not be given in real-time anymore.

$x(\cdot)$ is the (usually high-dimensional) trajectory of this system. One could think of the trajectory $x(\cdot)$ as the output of an array C_1, ..., C_m of subsystems of the liquid which define the continuous state vector.

Universal computational power of LSMs

We now want to characterize which mappings from input time series to output time series (i.e. which filters) can be computed by LSMs. Can only linear filters be implemented with a LSM or is it also possible to implement complex non-linear filters with an LSM?

In fact it turns out that there are only very weak restrictions on what LSMs can compute: a mathematical theorem [5] states that any time invariant filter with fading memory can be approximated with arbitrary precision by an LSM. The condition that only time invariant filters can be computed just exclude such exotic filters where a simple time shift of the input causes not only a time shift of the output but also a different time course of the output. Also the restriction to filters with fading memory is rather weak: it only states that an LSM can not compute a filter that is discontinuous, or whose output strongly depends on infinitely long input histories. Hence one may argue that the class of time invariant filters with fading memory includes practically any relevant filter from a biological as well as from an engineering point of view. From this perspective one could say that LSMs have universal computational power for computations on time series.

Only two abstract and conceptually simple properties have to be met to endow LSMs with such universal computational power for computations on time series: The class of components from which the liquid is composed satisfies the point-wise separation property and the class of functions from which the readout maps are drawn, satisfies the approximation property:

Separation Property: All output-relevant differences in the preceding part of two input time series $u_1(\cdot)$ and $u_2(\cdot)$ (before time t) are reflected in the corresponding liquid states $x_1(t)$ and $x_2(t)$ of the system.

Approximation Property: The readout has the capability to approximate any given continuous function f that maps current liquid states $x(t)$ on current outputs $v(t)$.

Implementing specific target filters

The preceding results provide a new conceptual framework for analyzing computations on time series, such as spike trains. However they do not yet address the question how to implement an LSM such that it approximates a given target filter. One approach which directly emerges from the LSM model is described in Fig. 4.

1) Choose a suitable liquid
2) Record liquid states $\boldsymbol{x}(t)$ at various time points in response to numerous different (training) inputs $\boldsymbol{u}(\cdot)$
3) Apply a supervised learning algorithm to a set of training examples of the form $\langle \boldsymbol{x}(t), y_u(t) \rangle$ to train a readout function f such that the actual outputs $f(\boldsymbol{x}(t))$ are as close as possible to $y_u(t)$

Fig.4: *A general approach for implementing specific target filters with a LSM. $y_u(t)$ denotes the output of the target filter at time t if its input is $u(\cdot)$.*

If the liquid fulfills the separation property and the readout function fulfills the approximation property, this procedure leads to an implementation of a LSM which approximates the given target filter. One advantage of this simple procedure is that it is not necessary to take any temporal aspects into account for the supervised learning task, since all temporal processing is done implicitly in the liquid. Another benefit of this procedure is that one can easily implement several target filters in parallel using the same liquid. One just has to train for each target filter a separate readout function.

Despite its simplicity the above procedure has one drawback: it does not specify which liquid and which learning algorithm one should choose to implement a given filter. For example, from a theoretical point of view it would suffice to choose the components of the liquid as a suitable collection of delay lines and to use a quite powerful readout (e.g. a artificial neural network, see e.g. [3] for regarding the details of this approach). On the other hand, one of the empirically most successful approaches in machine learning (support vector machines, see [6]) is based on the observation that almost all practically relevant classification tasks can be carried out by a single perceptron if the inputs are first projected into a very high dimensional space. In the framework of LSMs this implies that if the liquid transforms the inputs into a proper space of liquid states, a very simple readout will suffice to implement the given target filter. Hence there is a trade-off between the complexity of the liquid and the complexity of the readout. The optimal point for this trade-off depends on several factors, such as the type and number of target filter which one wants to implement.

Applications of the LSM approach

Computations on spike trains in recurrent neural microcircuits

In [1] it was explored how well the LSM approach is applicable to computations in models of neural systems. The main issue investigated was how well small recurrent neural circuits can be understood as a „liquid“. A „liquid“ in the sense that such circuits function as a universal integrator of a variety of stimuli.

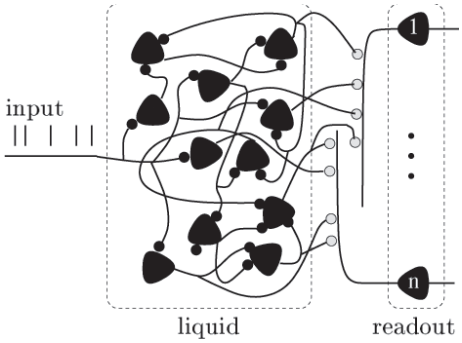


Fig.5: *The basic network model investigated in [1]. A randomly connected network of biologically quite realistic model neurons was employed as „liquid“. The readout function was implemented by another population of model neurons that received input from all the „liquid-neurons“. During training for a particular task only the synaptic strengths of the connections from the „liquid“ to the readout (open circles) are modified.*

The basic network model used in [1] is shown in Fig. 5. A randomly connected network of biologically quite realistically model neurons was employed as „liquid“. The input to this network was via several spike trains. The readout function was implemented by another population of model neurons that received input from all the „liquid-neurons“. The fraction of neurons firing around time t was interpreted as the output of the readout. Using the general training procedure described in Fig. 4, a readout function is trained to a specific task by adjusting the synaptic strengths of the connections from the „liquid“ to the readout. To accomplish this task a recently developed supervised learning algorithm called p-delta rule was used (see [7] for details about this learning algorithm).

All readout functions trained in this manner used the same recurrent microcircuit (liquid) as (universal) source of information to compute the desired output. The tasks assigned to the diffe-

rent readout maps were chosen such that each one had a focus on another aspect of the input. Results of computer simulations show that such models of neural microcircuits can indeed function as an optimal liquid since all considered tasks can be performed with quit high accuracy. Furthermore the issue how different connectivity structures of neural microcircuits affect the „usefulness of the liquid" was explored. It turned out that there exists some optimal regime of connectivity parameters for the neural microcircuit. Optimal in the sense that inputs are integrated (mixed) into the liquid state such that the considered computational tasks were performed with maximal accuracy. In other parameter ranges either the inputs are not integrated (mixed) at all and hence no information about past inputs is available in the liquid state, or the circuits exhibit a chaotic behavior. If the circuit exhibits chaotic behavior even the smallest change in the input (which causes only small changes in the target output) causes the liquid to end up in a totally different state, and hence the readout is usually not able to map such totally different states to rather identical outputs.

These approach provides a new platform for investigating through computer simulations the structure and function of neural microcircuits, for example to explore the computational advantages of the extreme complexity and diversity of neurons, synapses, and specific connectivity patterns found in the microcircuity of the brain.

Computations on spike trains in feedforward networks

Whereas in [1] recurrent circuits of spiking neurons were considered, in [8] a much simpler type of liquid is investigated; see Fig. 6.

The liquid was just an array of biologically realistic synapse models. It is known that synapses are quite heterogeneous, i.e. produce quit different outputs for the same input spike train, even within a single neural circuit. In fact these differences, which also vary from synapse to synapse, can serve as short term memory for a neural system, since the amplitude of the postsynaptic response for the current spike contains information about the preceding part of the spike train. Hence the parameters for the model synapses employed as liquid were drawn from distributions in accordance with empirical results (see e.g. [9]). The readout was implemented as another pool of spiking neurons; as in [1]. However, to demonstrate that the LSM approach allows to construct circuits which implement given mappings from input spike trains to output spike trains the firing activity of

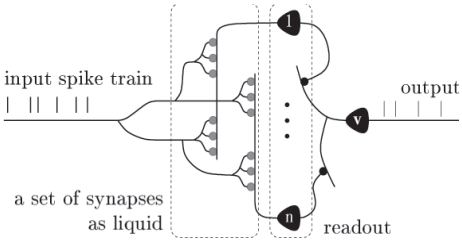


Fig.6: *The network of spiking neurons used in [8]. The liquid consists of an array of biologically realistic model synapses. As in [1] the readout is another population of neurons. Its firing activity is explicitly transformed into a spike train by the output neuron v. Networks of this type can be trained to behave like any given small finite state machine.*

the readout pool was explicitly transformed into a spike train using an extra single output neuron; see Fig. 6.

The question explored in [8] was to what extent such a simple neural circuit can carry out arbitrarily complex computations on spike trains. It was demonstrated by computer simulations that such a simple neural circuit can be trained to behave like any given small finite state machine. Finite state machines (FSM) are frequently used in computer science as general purpose models for computations on time series. A FSM usually gets a bit-string as input and produces as online output again a bit-string (in our terminology it is a filter which operates on bit strings).[3]

Since the finite state machines which were used as target for the training were drawn randomly, this result demonstrates impressively the generality of the LSM approach. Furthermore these results show that the heterogeneity of synapses enables a simple network of spiking neurons to perform quite complex computational tasks. This might be understood as a hint why the diversity of neurons and synapses found in real neural system may be computationally advantageous.

Computations on analog time series

The main idea of the LSM was independently discovered in [2]. The author of [2] considered an artificial recurrent neural network (see e.g. [3]) as liquid.[4]

As a readout function he used a single unit of the same type as the liquid is composed of. Training of this single output unit amounts to a linear regression problem, which is one of the simplest „learning" algorithms one can think of.

The perspective taken is mainly that of mathematics and engineering, where a recurrent network is seen as a computational device for realizing a dynamical system (the liquid). Hence the target filters (learning tasks considered) are from a different nature as presented so far. For example it is demonstrated that the quasi-benchmark task of learning a chaotic attractor can be accomplished by using the training approach depicted in Fig. 4. Another challenging task which could be solved in this way is the design of a controller for a pendulum (private communication; not reported in [2]).

The most appealing features of this learning algorithm for recurrent neural networks (which emerges from the LSM model) compared to others (see e.g. [3]) are its simplicity and robustness. These features stem from the fact that only the parameters of a single unit are trained and that this training can be done using linear regression.

Summary

We have discussed a novel computational model for analysing computations on time series in particular on spike trains: the „liquid computer" or more formally the liquid state machine. In contrast to models that are inspired by the architecture of the current generation of artificial computing machinery it requires no storage of information in stable states. We have formulated two simple conditions, the separation property and the approximation property, which together endow liquid computers with virtually unlimited computational power in the time series domain. On a more practical level the LSM approach provides a general method for training a computer model of a neural microcircuit consisting of biologically realistic models for neurons and synapses, to carry out basically any given computation on spike trains. Furthermore this general method can also be applied in the domain of artificial neural networks [2] and yields a simple and robust learning algorithm. Applications of this general method were discussed in Section 3.

To make the work on the LSM approach more accessible to other people we are currently setting up web resources (accessible via www.lsm.tugraz.at) regarding data, computer models, and analysis tools for neural microcircuits, which will be functional by fall 2002. In this webpage we will collect data on the anatomy and physiology of neural microcircuits

3 Note that bit-strings can easily converted to spike trains and vice versa. Hence it is possible to compare a FSM and the network depicted in Fig. 6.

4 The network they used consists of N units. At time step t unit i computes the output $x_i(t+1) = \tanh(\sum_j w_{ij} x_j(t))$ where w_{ij} is a parameter describing the connection strength between unit i and j.

from the lab by Markram (see http://www.weizmann.ac.il/neurobiology/labs/markram/markram.html) and others. Furthermore it will provide software for computer models of neural microcircuits that are built according to these data, as well as files with inputs for these circuits and tools for analyzing the circuit outputs. In addition it will offer implementations of learning algorithms by which the readout neurons from these circuits can be trained. In this way the user can not only carry out his/her own computational tests with these circuit models, but can also investigate the merits of the LSM framework.

References

[1] W. Maass, T. Natschläger, and H. Markram. Real-time computing without stable states: A new framework for neural computation based on perturbations. submitted for publication, 2001. electronically available via http://www.igi.TUGraz.at/tnatschl/psfiles/130.pdf.

[2] H. Jaeger. The „echo state" approach to analysing and training recurrent neural networks. GMD Report 148, German National Research Center for Information Technology, 2001. electronically available via ftp://borneo.gmd.de/pub/indy/publications_herbert/EchoStatesTechRep.pdf.

[3] J. Hertz, A. Krogh, and R. G. Palmer. Introduction to the Theory of Neural Computation. Addison-Wesley, 1991.

[4] S. H. Strogatz. Nonlinear Dynamics and Chaos: With Applications in Physics, Biology, Chemistry, and Engineering (Studies in Nonlinearity). Addison-Wesley, 1994.

[5] W. Maass and H. Markram. On the computational power of recurrent circuits of spiking neurons. submitted for publication, 2001.

[6] V. N. Vapnik. Statistical Learning Theory. John Wiley, New York, 1998.

[7] P. Auer, H. Burgsteiner, and W. Maass. The p-delta learning rule for parallel perceptrons. submitted for publication, 2001.

[8] T. Natschläger and W. Maass. Spiking neurons and the induction of finite state machines. Theoretical Computer Science: Special Issue on Natural Computing, 2002. electronically available via http://www.igi.TUGraz.at/tnatschl/psfiles/fst-learning-tcs.pdf.

[9] A. Gupta, Y. Wang, and H. Markram. Organizing principles for a diversity of GABAergic interneurons and synapses in the neocortex. Science, 287:273-278, 2000. ■

Dr. Thomas Natschläger, computer scientist, Ph.D. under Prof. W. Maass, University Assistant at the Institut für Grundlagen der Informationsverarbeitung der TU Graz.
Homepage: http://www.igi.tugraz.at/tnatschl

Prof. Dr. Wolfgang Maass, computer scientist and mathematician, Ph.D. under Prof. K. Schütte (Mathematical Logic) at the University of Munich, 1986-1991 Professor at the University of Illinois (Chicago), since 1991 Professor at the TU Graz, since 1992 Head of the Institut für Grundlagen der Informationsverarbeitung der TU Graz. Homepage: http://www.igi.tugraz.at/maass

Prof. Dr. Henry Markram, graduate student of Prof. R. Douglas at the University of Cape Town (South Africa), Ph.D. under Prof. M. Segal at the Weizmann Institute for Science in Rehovot (Israel), since 1998 Professor in the Department of Neurobiology at the Weizmann Institute for Science, since 2002 Director of the new Brain Mind Institute at the Ecole Polytechnique Federale de Lausanne (EPFL).
Homepage: http://www.weizmann.ac.il/neurobiology/labs/markram/markram.html

The Relevance of Understanding Brain Computation

Rodney Douglas, Kevan Martin
Institute of Neuroinformatics, ETHZ/UNIZ Zürich

Introduction

Information technologies will dominate every level of the industrial and service economies for the foreseeable future. At the turn of the century, the world expenditure on Information Technologies was approximately $ 1 trillion per annum (much larger than all expenditure on Health, for example.). This huge expenditure is focused on technology that is explicitly programmed by man and has very little autonomous learning and intelligence.

One major growth area in IT will be the development of intelligent systems that can learn to interact successfully and reliably with the real world, and that require a minimum of human supervision. This development will be based on the study of natural computation in biological intelligent systems.

Brain models and Technology

Since the Age of the Enlightenment, our models of the human brain have always been analogies of the most advanced physics and technology of the day. Thus, the physics of fluid mechanics, electricity and magnetism, field theories, information theory, and the technology of hydraulics, clockwork automata and telephone exchanges, have at different times shaped our views about how our brain works. This pattern has continued up until the present, as the digital computer and communication technology provide the layman and expert alike with ample analogies for brain structures and function.

The enormous sophistication of present day computer and communication technology has also placed new demands on brain scientists. Why is this? The mobility, autonomy, intelligence, robustness, speed and low power consumption that consumers expect from modern computer and communication technology have obvious and direct relationships to brains, which have just all of these attributes. Some brain scientists have now realized that while previously their work was justified largely by the potential benefits to medicine, in the future major application of brain research could be in the Information Technology (IT) industry.

What is being done to meet this future expectation? Well - almost nothing. Neither the IT industry or academic brain science has shown much interest in each other, despite the great potential they offer in collaboration. Part of this lack of interest is that over the past 40 years the IT industry has already benefited enormously from the advances made in artificial intelligence (AI) and no doubt expects this to continue in the future. However, in the rapidly evolving IT industry, one should be cautious about such extrapolations. For example, the explosive growth of cellular communication and the Internet has, in a very short time, changed the game for both brain science and for traditional AI. Traditional AI has struggled to make in-roads is in the important 'real-world' areas like speech and text recognition. It has been an uphill battle to create functional perceptuo-motor systems, which would be competent enough, for example, to navigate an automobile at 120kph down a highway and react appropriately to road signs designed for humans. Solutions to the many problems in controlling complex environments, such as building, remain strikingly primitive. A truly intelligent building is still science fiction.

Promise of Neurotechnology

There is strong pressure to adapt conventional IT approaches to fit the current consumer demands. But, something much more visionary is required if radical solutions are to be found to meet the very high expectations the current technology revolution has generated. A very promising and practical approach to achieving such radical solutions is to explore the engineering solutions that Nature has evolved over millions of years.

Nature has given us models and endless examples of agents that carry out extraordinary performances, such as navigation, foraging and communication, using devices that are tiny (e.g. the brain of a honey-bee weighs 1mg) with an efficiency that is unmatched by any human-built machine. In areas other than brain and computation we have successfully applied lessons learned from complex natural models before (flight being just one example) and again we are presented with an opportunity to use basic scientific knowledge of the brain to achieve undreamed of solutions to a very wide swathe of problems facing the society of the 21C.

Investing in Neurotechnology

Little is being done to connect brain research with IT. The reasons are not hard to find - government funding agencies have always associated brain research with medical health and they demand that even basic research be justified by its potential advances to mental health. This is the case worldwide, and Europe is no exception. It is left therefore to individual scientists and private companies to create the links that are necessary to exploit the potential of a new field that combines brain science with IT in applications in novel domains - e.g. the construction and automotive industries.

In the case of the brain we have already built in silicon, artificial neurons, and have moved onto the next stage where the real advance will come from understanding how hundreds or millions of neurons are connected and act together in networks to produce a given behavior. Such neuromorphic systems are in embryo, but there are promising indications of growing success.

What is required now, is a more general constructive understanding of natural intelligence: One that provides for the principled synthesis

of large neuromorphic systems, in a manner analogous to the powerful constructive understanding that has driven the digital computer industry. The development of such a formalism for the construction of biological (or organic) style computers, would lead to an explosion of low-cost autonomous intelligent systems for use in (for example) motor vehicles, intelligent buildings, home automation, the entertainment and leisure industries, and in a variety of robots that are necessary for exploration, mining, and maintenance. ■

Prof. Dr. Rodney Douglas, neuroscientist with particular interest in neural computation and neurotechnology, Director of the Institut für Neuroinformatik at the ETH and Universität Zürich. Homepage: http://www.ini.unizh.ch
Prof. Dr. Kevan Martin, neuroscientist, Professor for Neurophysiology at the Institut für Neuroinformatik at the ETH and Universität Zürich. Homepage: http://www.ini.unizh.ch

Veranstaltungen

zusammengestellt von Klaus D. Zesar

06.06.-08.06.	**ECIS'02:** The 10th European Conference on Information Systems, Gdansk (Poland), http://www.bg.univ.gda.pl/ecis2002
10.06.-13.06.	**ACIT '02:** International Conference on Automation, Control, and Information Technology, Novosibirsk (Russia), http://www.iasted.org/conferences/2002/russia/acit.htm
13.06.-14.06.	**PPPJ '02:** Principles and Practice of Programming in Java, Dublin (Ireland), http://www.cs.tcd.ie/pppj
14.06.-16.06.	I**AK'02:** International Conference on Logic and Knowledge, Darmstadt (Germany), http://www.mathematik.tu-darmstadt.de/ags/ag1/lak01
17.06.-21.06.	**Ada-Europe'02:** 7th International Conference on Reliable Software Technologies, Vienna (Austria), http://www.ada-europe.org/conference2002.html
17.06.-20.06.	**IEA/AIE'02:** Fifteenth International Conference on Industrial & Engineering Applications of Artificial Intelligence & Expert Systems, Cairns (Australia), http://iea2002aie.bsee.swin.edu.au/
19.06.-21.06.	**LCTES '02 - SCOPES '02:** Joint Conference on Languages, Compilers and Tools for the Embedded Systems, Berlin (Germany), http://www.edaa.com/lctes-scopes02/
19.06.-21.06.	**CA'02:** 15TH International Conference on Computer Animation 2002, Geneva (Switzerland), http://miralabwww.unige.ch/ca2002/
24.06.-27.06.	**HPC 2002:** High Performance Computing: Technology and Applications, Cetraro (Italy), http://www.parcolab.unical.it/hpc2002/index.htm
24.06.-29.06.	World Conference on Educational Multimedia, Hypermedia and Telecommunications, Denver CO (USA), http://www.aace.org/
25.06.-28.06.	**DIS 2002:** Designing Interactive Systems 2002, London (United Kingdom), http://www.acm.org/sigs/sigchi/dis2002/
25.06.-28.06.	**ASM 2002:** International Conference on Applied Simulation and Modelling, Crete (Greece), http://www.iasted.org/conferences/2002/greece/asm.htm
25.06.-28.06.	**SPPRA '02:** 2nd International Conference on Signal Processing, Pattern Recognition, and Applications, Crete (Greece), http://www.iasted.org/conferences/2002/greece/sppra.htm
27.06.-28.06.	**WOON'02:** The 6th International Conference on Object-Oriented Technology, Saint-Petersburg (Russia), http://woon.eltech.ru/
09.07.-13.07.	**GECCO'02:** Genetic and Evolutionary Computation Conference, New York NY (USA), http://www.isgec.org/gecco-2002
10.07.-12.07.	**IV'02:** 6th International Conference on Information Visualisation, London (United Kingdom), http://www.graphicslink.demon.co.uk/iv02
15.07.-19.07.	**ICCS'02:** 10th International Conference on Conceptual Structures, Integration and Interfaces, Borovets (Bulgaria), http://lml.bas.bg/iccs2002

Fortsetzung auf Seite 50 ▶

Stimulus Meets Simulus - Thoughts on the Interface

Hans H. Diebner, Peter Weibel
Center for Art and Media, Karlsruhe, F.R.G., and
Neue Galerie Graz

Abstract

Our thoughts on the interface expressed in this paper are based on Rizzolatti's roughly six year old findings, namely the experimental evidence for the existence of „mirror neurons", as well as on recently published models for cognitive systems that are capable to simulate. We review the main aspects of that cognitive system and interpret how the system itself may be brought to interpret. This is in line with Erdi's point of view that the human brain is a hermeneutic device which is, to rephrase Tsuda, our interpretation of how the brain interprets.

Introduction

Certainly, we, that is (essentially) our brains, are autonomous optimizers [1, 2, 3]. We try to change the environment so as to make it more tractable for us - using fire and fist wedges, for example. Particularly sophisticated tools are artificial intelligent systems. Already existing neural networks failed to copy brains, so far. Our goal is to construct artifical brains that mimick as accurately as possible the functionality of human brains. Artificial (humanoid) brains may be good for exploitation in the same sense as humans make extensive use also of other humans (or agents in general) in order to organize their lifes [4]. One may ask what this is good for. Why do we not use our already available fellow men and search for brain prosthesis that really complete our thinking organ instead? Anyhow, a really good model of a brain nevertheless would most likely do nothing different than likewise building artifical brains. Thus, why do we do it? Quite simply, it is an addiction!

To be frank, we are a million miles away even from a rudimentary copy of a human brain. Additionally, there are legitimate doubts that characteristics which we associate with consciousness can be at all artificially produced. Finding out the boundaries of cognition research, as well as understanding the human brain and consciousness, represents an excellent reason for this research direction for itself.

As it becomes evident from the above, we orient ourselves regarding the cognition research at the mode of operation of the brain. However, we are free to model in a rather abstract way, i.e. we worry not too much about physiological details. For example, we orient ourselves substantially at what Rizzolatti et al. [5, 6] call „mirror neurons" which is indeed an experimental result and validates our proceed. Social conscience and empathy, the perhaps most important characteristics of humans, may be explained by means of mirror neurons. Even earlier, in a more abstract manner, Rössler [1, 2, 3, 7] discussed the principle of ultraperspective, which is the capability to step into the shoes of another, or to escape from autism on the basis of brains that are capable to simulate.

To be more specific, we report on a recently published adaptive network for the recognition of external dynamics [8, 9, 10, 11]. The internal representation thereby is able to simulate and thus has predictive potential very much like we are able to estimate whether we can safely cross the street when a car approaches. However, quite frequently we have to react to sudden changes in the external dynamics. The alternation between „stimulus" and „simulus" leads to a continuous update of the internal representation of the dynamics which in turn can be used for simulation. In other words, the proposed system allows for an „on the fly" adaptation and, thereby, performs the hermeneutic cycle [12, 13, 14].

Chaotic Itinerancy

Assume given a nonlinear dynamical system like the Rössler system, for instance:

$$\begin{aligned} \dot{x} &= -y - z \\ \dot{y} &= x + 0.2y \\ \dot{z} &= 0.2 + xz - \alpha z \end{aligned} \qquad (1)$$

Through the variation of the parameter α, for example, a cascade of period-doupling sequences into chaos can be passed through. In other words: to each value of α corresponds a different dynamical behavior of the system. Fig. 1 shows a computed time series of the x variable of Rössler's system in the chaotic regime with $\alpha = 5.9$. Assume now that α itself obeys a differential equation that adds to Eqn. 1. Then the subsystem given by Eqn. 1 undergoes an itinerancy between attractors that depends on the concrete time course of α as well as on the bifurcation behavior of the system in hand. As an example, the system may switch from a specific limit cycle to a chaotic attractor. Strictly speaking, it is in this case no longer fully justified to speak of attractors. Anyway, since the proton seems to be the only known example for a substructure of the Universe that has a half-life period perhaps larger than the momentary age of the Universe the concept of an attractor is a practical one only with respect to either a proper time or a space scale. To be apparently confronted with constant parameters may also be due to the fact of being intrinsic observers. The introduction of virtually constant parameters which leads to attractors, for example, is what we usually call reductionism[1]. Whether we have to loosen the strict constancy of the parameters depends on the spatial and/or the temporal scale at which the system is treated. We are so free as to add the philosophical speculation whether the equation of motion of the whole Universe is a parameter-free one which is especially important if one regards time itself as a parameter [15].

In a large array of coupled systems of the Rössler type, for example, or any other low-dimensional dynamical system, a rich reservoir of

1 whereof Florian Grond convinced us in a private communication

possible (sub-) attractors that can be passed through by varying one or more parameters is easily imaginable. This reminds us on the chaotic itinerancy brain model of Kaneko, Nicolis and Tsuda [16, 17, 13]. Additionally, through the dynamical description of the parameters a second order cybernetics can be introduced, i.e., a description of cognition and perception by means of an interaction between brain and the rest of the world [9]. The thereby constructed reality can be seen as eigenstates of the brain as especially Luhmann [18] pointed out. In the cognitive model presented in [8, 9, 10, 11] and reviewed in the following the interaction between the system and the external world is modeled by means of a force control mechanism. This force control in principle allows for, besides the impact of the observed external world on the system, a self-modification of the cognitive apparatus. These characteristics can be related to creativity and the hermeneutic cycle [12]. The permanent conversions of the cognitive system due to external and internal control leads to a continuous update of the simulation. The stimulus-simulus relationship can be seen as a specification of the complementarity principle [1, 19]. The stimulus is built up by the external reality and comprises the efferenz and afference principle, the basis for the cultivation of locomotion strategies, for motor activity and action directives, and, especially important for human beings, the interpretation of the world.

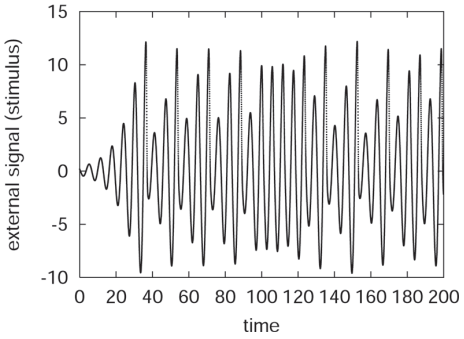


Fig.1: *The x-variable by time of the Rössler system of Eqn. 1 with α chosen to be 5.9.*

The scheme of our system is depicted in Fig. 2. To the left, we have an external dynamics (the stimulus) which is „perceived“ by the system. To the right, we see the representation of the external dynamics as a „mirror“. This dynamics is the simulative part of the system (simulus). The kernel of the system is a pool of dynamical modules each of which is controlled by the external dynamics. The pool of internal systems is shown in the middle part of Fig. 2 as a stack of six modules, where six is an arbitrary number. The strength of the control term, which is explained in detail in the following section, serves as a measure of „fitness“ of the corresponding module. The parameters of the modules are used in a superpositional manner weighted by their „fitness“ to build up the parameter of the simulus. In the scheme depicted in Fig. 2 the modules D_3 and D_4, for example, fit best to the stimulus and, therefore, contribute with a larger weight (bold arrows) to the construction of the simulus. D_1 and D_6, for example, fit worse and contribute less (dashed arrows) to build up the simulus.

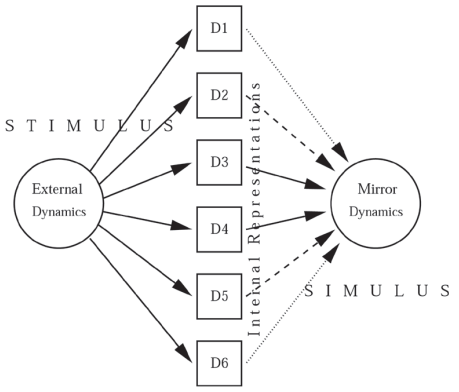


Fig.2: *Scheme of the adaptive system.*

Since it seems to be very unlikely that nature uses complicated regression algorithms we have to search for a plausible and easily implementable mechanism. We suggest to use a mechanism that is based on the chaos control method derived by Pyragas [20]. It has been shown that this method has a strong evidence to be found in brain dynamics [21, 22, 23]. Furthermore, it has been shown that Pyragas' method can be derived from diffusive coupling of chemical reactors in a limit which is a further indication for its natural application [24].

Brief Recapitulation of Pyragas' Control Method

The external force control method introduced by Pyragas [20] in its original form deals with the stabilization of unstable periodic orbits in non-linear dynamic systems in the chaotic regime. Control is achieved by adding a „control term“ (which is proportional to the difference between a variable of the system and the corresponding projection of the unstable periodic orbit to be stabilized) to the corresponding differential equation of the system. This method is able to stabilize unstable periodic orbits of the system with an - in the long run - vanishing control term. In the following we deviate slightly from this original application by using Pyragas' control method for the synchronization of two dynamical systems and refraining from being able to stabilize with an almost vanishing control term. Assume x and x´ to be the states of two dynamical systems of the same dimension n and the same dynamics f which are given by the differential equations

$$\begin{aligned} \dot{x} &= f(x;\beta), & \beta &= (\beta_1,\beta_2,...,\beta_m) \\ \dot{x}' &= f(x';\beta'), & \beta' &= (\beta_1',\beta_2',...,\beta_m') \end{aligned} \quad (2)$$

where β and β' are sets of fixed parameters. If now the difference of at least one (appropriate) pair of corresponding variables (say the first) multiplied by a suitable chosen factor K is added to the unprimed system

$$\begin{aligned} \dot{x}_1 &= f_1(x_1,x_2,...,x_n;\beta) + K(x_1' - x_1) \\ \dot{x}_2 &= f_2(x_1,x_2,...,x_n;\beta) \\ &\vdots \\ \dot{x}_n &= f_n(x_1,x_2,...,x_n;\beta), \end{aligned} \quad (3)$$

this unprimed system will be forced to the dynamics of the primed controlling system, at least if the difference of the dynamics is not too extreme [25]. The value of the control term $K(x_1'-x_1)$ may be used as a measure for the quality of the control. As in the original application of Pyragas' method, this control term will be negligible in a long term if the difference of the system parameters is relatively small.

The Functionality of the Adaptive System

In order to describe the mechanism of the adaptive system we simplify matters by using the timeseries of the x-variable (Fig. 1) of Rössler's system (Eqn. 1) as a given external signal (the stimulus). We use the subscript *E* attached to the variables as well as to the parameters to refer to „external“ whereas the later introduced internal modules and the simulus are differently labeled. The value of α_E is chosen to be 5.7 in the following.

Now we choose six further Rössler systems with parameters

$$\begin{aligned} \alpha_1 &= 5.64, & \alpha_2 &= 5.66, & \alpha_3 &= 5.68, \\ \alpha_4 &= 5.72, & \alpha_5 &= 5.74, & \alpha_6 &= 5.76 \end{aligned} \quad (4)$$

to constitute a pool of internally given dynamical types. Each of these internal dynamics is forced to the external timeseries by means of

$$\begin{aligned} \dot{x}_i &= -y_i - z_i + K(x_E - x_i) \\ \dot{y}_i &= x_i + 0.2\,y_i \\ \dot{z}_i &= 0.2 + x_i z_i - \alpha_i z_i; \qquad i = 1,2,...,6 \end{aligned} \quad (5)$$

where K is a coupling constant which is choosen to be 1 in the following. The internal modules are schematically depicted as a stack of six squares in Fig. 2.

The absolute values of the six control terms,

$C_i(t) = |x_E - x_i|$, are used to indicate how good the modules mimick the behavior of the external dynamics. A large control term indicates that the module's dynamical behavior strongly deviates from the external one and vice versa. Figure 3 shows the index (corresponding to the subscripts used in Eqn. 4) of the dynamical module that has the smallest control term versus time. One clearly sees that after the transient time, the most frequently chosen module is system 4, i.e., the system with the parameter value closest to that one of the external signal. Events of desynchronization where other modules seemingly match better occur extremely rarely. The initial conditions of system 1 have been chosen equal to that one of the external system which explains that system 1 has the smallest control term in the beginning.

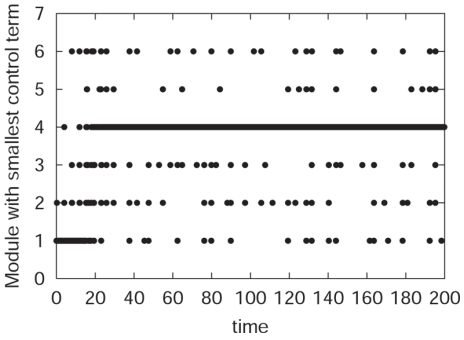


Fig.3: *Index of the module out of the internal pool which has the smallest control term versus time. After the transiency in the beginning the most frequent „switched on" module is system 4 which has the parameter closest to that one of the external (stimulus) system.*

The idea now is to use the reciprocal absolute values of the control terms as measures for whether the external dynamics match or clash the internal modules and to build up a new module with that information. We call the new module „mirror system" which indeed can serve as a simulus after the adaptation to the external dynamics. For the time being we fix the dynamical type of the mirror system to the Rössler-type as given in Eqn. 1. We take up the position that only the value of the parameter α is unknown. To distinct the mirror system from the external dynamics and from the modules we indicate all variables and the parameter with the subscript *M*. Due to the above thoughts it is evident that the update $\alpha_M(t + \Delta t)$ of the parameter value of $a_M(t)$ is essentially given by a linear combination of the form $\frac{s}{C_M(t)}\alpha_M(t) + \sum_{i=1}^{n}\frac{1}{C_i(t)}\alpha_i(t)$ together with a proper normalization term. The first term is a „self-affirmation" term where the parameter *s* has a smoothing impact on the adaptation which avoids occasional desynchronization and, therefore, reduces fluctutations of α_M.

The translation into a differential equation leads to the following time behavior of α_M:

$$\dot{\alpha}_M = \frac{\sum_{i=1}^{n}\frac{1}{C_i(t)}(\alpha_i(t) - \alpha_M(t))}{\frac{s}{C_M(t)} + \sum_{i=1}^{n}\frac{1}{C_i(t)}}, \qquad (6)$$

Of course, one has to take care that each C_i has a finite value by using $C_i(t) = \max\{\varepsilon, |x_E - x_i|\}$, for example, with a small ε. In the subsequently presented simulation we use a pool which consists of $n = 10$ modules. The parameters of these modules have been chosen to be (from α_1 through α_{10}): 5.71; 5.76; 5.81; 5.86; 5.92; 5.96; 6.01; 6.06; 6.11; 6.16. The external parameter has now been chosen to be $\alpha_E = 5.9$.

As can be seen in Fig. 4, the adaptation works extremely well, especially given that we deal with a chaotic system. To demonstrate the impact of the self-affirmation parameter s we present the results of four adaptation runs with $s = 10$, 35, 100 and 300, respectively. A value of s = 10 leads to a sustaining oscillatory behavior of α_M as well as to an over-estimation. A value for *s* greater than 35 leads to an accurate adaptation. The velocity of convergence decreases if *s* increases further.

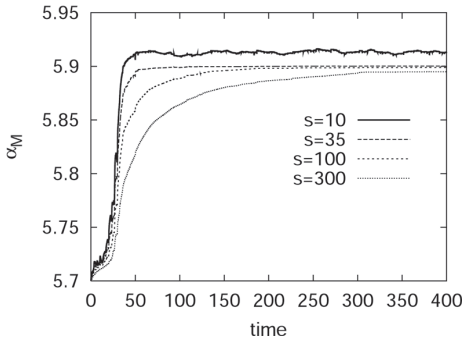


Fig.4: *Parameter adaptation using the differential equation of Eqn. 6. The values of the „self-affirmation" parameter have been chosen to be s = 10, s = 35, s = 100 and s = 300, respectively, which are marked correspondingly in the graph. An increasing value for s leads to a smoother curve on the cost of adaptation velocity.*

Applications to Measured Signals

So far we dealt with an oversimplified case in order to introduce the functionality of the adaptive system. The dynamical type of the stimulus has been known and the internal modules that have been used to build up a simulus were of the same type as the stimulus. We took up the position that only a single parameter was unknown and had to be estimated. In „real life", of course, the dynamical type of the stimulus is usually unknown. Even worse, we are faced with the cardinal problem of identity. How to model a dynamics will always remain a matter of experience and momentary knowledge, which is why we already referred to hermeneutics [12, 14]. In a recent paper [9] we applied the system to a measured signal (a human pulse). As internal modules we used van-der-Pol oscillators and adapted with respect to two parameters. These two parameters define a class of van-der-Pol oscillators. The simulus was able to relatively accurately mimick the real dynamics and has to be interpreted in the following way: it is that system out of the given class of modules which mimicks the external dynamics best in the sense of minimizing the force control term. The way the system has been applied so far did not allow to search and adapt to dynamical types other than the van-der-Pol oscillator.

A major achievement would be to construct an adaptive system that allows for the adaptation of the dynamical type itself. A chaotic oscillator, for example, can be fragmented in linear (harmonic oscillator) parts and non-linear switch elements. It has been shown by Sahle and Baier [26] as well as by Meyer [27] that such a decomposition into basic elements can be used to construct generalized Rössler systems in arbitrary dimensions. The idea to use such basic elements also in view of an application within the framework of adaptive systems suggests itself. We are confident to find a decomposition that allows for the construction of arbitrary dynamical types. However, we expect to be faced with the problem of then being too universal and probably too complex which is to counteract in the same manner as scientists have to apply „occams razor" to reduce complexity. A combined optimization of adaptation time, adaptation goodness and system size may serve as an objective measure probably in relation to a Darwinian fitness.

Applications to Spatio-Temporal Patterns

The adaptation introduced so far is restricted in a further aspect namely we were concerned with one-dimensional (scalar) signals only. In a recent paper [11], however, we have been able to show that the adaptive system can be applied also to a spatio-temporal pattern forming system. Specifically, we simulated an array of 100 by 100 coupled oscillators each of which were of the Hodgkin-Huxley type. We refrain from going into technical details here and refer to the original publication instead. What we need to know here is the fact that the array of oscillators that

has been used as an external dynamics presented to the adaptive system showed self-excited spiral-pattern formation. The set of parameters of the internal modules in contrast have been chosen so that some modules showed self-excited pattern formation whereas others did not form patterns without explicit excitation by an additional signal. The parameters' values of the internal modules spaned a grid around the values of the external parameters. Each oscillator of the external array has been coupled by means of Pyragas' force control to the corresponding oscillator of the internal module as well as to that of the mirror system. The mirror has been adapted to the external array with respect to two parameters.

After a relatively short adaptation time the mirror system was able to simulate where the meaning of simulation became particularly vivid in this case. After the modules as well as the simulus has been decoupled from the external array the simulus remained in a synchronous state with the stimulus for quite a long time whereas the internal modules desynchronized. If one now assumes that each oscillator corresponds to a video pixel one may speculate whether a continuation even of a movie at least for a short time is possible. We dare to compare a drift of the simulus away from the reality into unrealistic events after decoupling (i.e. sonsory deprivation of) the cognitive system from the rest of the world with dreaming or hallucinating. A further speculation is the possibility to apply the system within the fields of interactive cinema. Given that the idea of hermeneutics holds, a further expectation is that an adaptive system like the one proposed above shows what is called „narrative knowledge". To put it simple, although our perception is limited by spatio-temporal locality we nevertheless get an impression of the whole only by the perception of single spatio-temporal extracts (scenes) that are glued together. This „connexionism" leaves much space for interpretation and has some similarity with the „binding problem" in neuro-physiology [28]. To enhance the proposed device for the usage in future cinema is a big but exciting challenge.

We mention in passing, that cognition cannot work without storage which, of course, also holds for the proposed cognitive system. It is straightforward, however, to regard the pool of internal modules as a memory since the mirror system can be fed into the pool or even treated as an internal pool member from the very beginning. Mutual force control applied to the internal modules lead to a self-modifying property. Each external stimulation leaves an internal pool of modules after the adaptation that can undergo internal control and modification processes that, with a grain of salt, may even introduce creativity escpecially after stochasticity is added to a certain degree.

Conclusions

We repeat our statement from above that we regard cognition and perception as a continuous alternation between stimulation and simulation. As a more allegoric statement we add that the „interpretation" takes place on the „interface" between the two specifications of complementarity that are tighly entangled. We are well aware that semantical and consciousness related aspects as interpretation and creativity are much more profound than we suggest when comparing with the functioning of our adaptive system. We therefore emphasize once more that we speak of an enormous potentiality that lies in the design of the proposed system which is at least true for technical applications. Insights to human social behavior and cognition may be gained in a multi-agent realization of the proposed cognitive system. We are confident that new properties that are much closer to human cognition arise when several of the adaptive systems are coupled.

Acknowledgement

The authors are grateful to Otto E. Rössler, Wolfgang Maass, Florian Grond, Sven Sahle, Christina Lindner, Axel A. Hoff, Horst Prehn, and Adolf Mathias for fruitful discussions.

References

[1] Otto E. Rössler. Adequate locomotion strategies for an abstract organism in an abstract environment - a relational approach to brain function. In Lecture Notes in Biomathematics, volume 4. Springer, Berlin, 1974.

[2] Otto E. Rössler. An artificial cognitive map system. BioSystems, 13:203-209, 1981.

[3] Otto E. Rössler. An artificial cognitive-plus-motivational system. Progress in Theoretical Biology, 6:147-160, 1981.

[4] Andy Clark. Being There: Putting Brain, Body, and World Together Again. MIT press, Cambridge, Mass., 1997.

[5] V. Gallese, L. Fadiga, and G. Rizzolatti. Action recognition in the premotor cortex. Brain, 119:593-609, 1996.

[6] G. Rizzolatti, L. Fadiga, V. Gallese, and L. Fogassi. Premotor cortex and the regognition of motor actions. Cognitive Brain Research, 3:131-141, 1996.

[7] O.E. Rössler. Ultraperspective and endo-physics. BioSystems, 38:211-219, 1996.

[8] Hans H. Diebner, Sven Sahle, and Axel A. Hoff. A realtime adaptive system for dynamics recognition. Chaos, Solitons & Fractals, 13/4:781-786, 2002.

[9] Hans H. Diebner, Axel A. Hoff, Adolf Mathias, Horst Prehn, Marco Rohrbach, and Sven Sahle. Towards a second cybernetics model for cognitive systems. Chaos, Solitons & Fractals, 13/7:1465-1474, 2002.

[10] Hans H. Diebner. A simulating cognitive system with adaptive capability. BioSystems, 64/1-3:141-147, 2002.

[11] Hans H. Diebner, Axel A. Hoff, Adolf Mathias, Horst Prehn, Marco Rohrbach, and Sven Sahle. Control and adaptation of spatio-temporal patterns. Z. Naturforsch. A, 56:663-669, 2001.

[12] Peter Erdi. The brain as a hermeneutic device. BioSystems, 38:179-189, 1996.

[13] Ichiro Tsuda. The plausibility of a chaotic brain theory. Behavioral and Brain Sciences, in print.

[14] Peter Weibel and Hans H. Diebner. Realität, Aktualität, Ästhetik und Interpretation. In Hans H. Diebner, editor, Studium generale zur Komplexität. Genista Verlag, Tübingen, 2001.

[15] Julian Barbour. The end of time - The next revolution in physics. Oxford University Press, Oxford, 1999.

[16] John S. Nicolis and Ichiro Tsuda. Mathematical description of brain dynamics in perception and action. J. Consci. Studies, 6:215-228, 1999.

[17] Kunihiko Kaneko and Ichiro Tsuda. Complex Systems: Chaos and Beyond. Springer, Berlin, 2001.

[18] Niklas Luhmann. Die Kunst der Gesellschaft. Suhrkamp, Frankfurt am Main, 1997.

[19] Horst Prehn. The neuro-loop: Biofeedback interfaces. In Hans H. Diebner, Timothy Druckrey, and Peter Weibel, editors, Sciences of the Interface. Genista-Verlag, Tübingen, 2001.

[20] Kestutis Pyragas. Continuous control of chaos by self-controlling feedback. Phys. Lett. A, 170:421, 1992.

[21] C. Skarda and W.J. Freeman. How brains make chaos in order to make sense of the world. Behav. Brain Sci., 10:161-195, 1987.

[22] A. Babloyantz and C. Lourenço. Computation with chaos - a paradigm for cortical activity. Proc. Natl. Acad. Sci. USA, 91:9027-9031, 1994.

[23] Axel A. Hoff. Chaos control and neural

classification. Z. Naturforsch., 49a:589-593, 1994.

[24] Axel A. Hoff, Hans H. Diebner, and Gerold Baier. Reversible control of chemical reaction systems. Z. Naturforsch., 50a:1141-1146, 1995.

[25] Axel A. Hoff. Chaoskontrolle, Informationsverarbeitung und chemische Reaktionssysteme. Logos Verlag, Berlin, 1997.

[26] Gerold Baier and Sven Sahle. Design of hyperchaotic flows. Phys. Rev. E, 51:R2712-R2714, 1995.

[27] Thorsten Meyer. Das Verallgemeinerte Rössler System. Master's thesis, University of Bayreuth, Lehrstuhl Experimentalphysik II, 1995.

[28] Axel A. Hoff. Chaoskontrolle im Gehirn. In Hans H. Diebner, editor, Studium generale zur Komplexität. Genista Verlag, Tübingen, 2001. ■

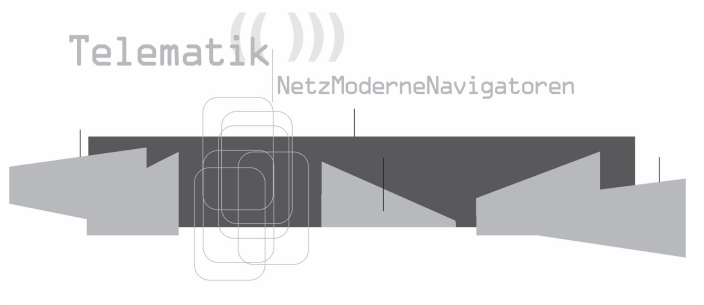
Dr. Hans H. Diebner, scientist and artist, Ph.D. under Prof. O. E. Rossler, heads the Basic Research Group at the Zentrum für Kunst und Medientechnologie (ZKM) in Karlruhe.
Homepage: http://diebner.de

Prof. Peter Weibel, artist and theoretician, Director of the Zentrum für Kunst und Medientechnologie (ZKM) in Karlsruhe, and Chefkurator of the Neue Galerie Graz.
Homepage: http://on1.zkm.de/zkm/personen/weibel

▶ Fortsetzung von Seite 45

15.07.-19.07.	**AAMAS '02:** The First International Joint Conference on Autonomous Agents and Multi-Agent Systems, Bologna (Italy), http://www.autonomousagents.org/2002/
17.07.-19.07.	**ASC '02:** 6th International Conference on Artificial Intelligence and Soft Computing, Banff AB (Canada); http://www.iasted.org/conferences/2002/banff/asc.htm
18.07.-20.07.	**ICIS'02:** 11th International Conference on Intelligent Systems on Emerging Technologies, Boston MA (USA), http://www.isca-hq.org/icis-2002-call
21.07.-26.07.	**SIGGRAPH '02:** The 29th International Conference on Computer Graphics and Interactive Techniques, San Antonio TX (USA), http://www.siggraph.org/s2002/
23.07.-25.07.	**KDD '02:** The Eighth ACM SIGKDD International Conference on Knowledge Discovery and Data Mining, Edmonton AB (Canada), http://www.acm.org/sigkdd/kdd2002/
06.08.-08.08.	Fiftheenth International Conference on Systems Engineering, Las Vegas NV (USA), http://www.icseng.org/
11.08.-15.08.	**SIGIR'02:** 25th ACM/SIGIR International Conference on Research and Development in Information Retrieval, Tampere (Finland), http://www.sigir2002.org/
12.08.-14.08.	**CGM '02:** 5th International Conference on Computer Graphics and Imaging, Kaua'I HI (USA), http://www.iasted.org/conferences/2002/hawaii/cgim.htm
12.08.-14.08.	**IMSA '02:** 6th IASTED International Conference on Internet and Multimedia Systems and Applications, Kaua'I HI (USA), http://www.iasted.org/conferences/2002/hawaii/imsa.htm
12.08.-14.08.	**SIP '02:** 4th IASTED International Conference on Signal and Image Processing, Kaua'I HI (USA), http://www.iasted.org/
09.09.-13.09.	**RE'02:** Joint International Requirements Engineering Conference, Essen (Germany), http://www.re02.org/
10.09.-12.09.	**iiWAS '02:** The Fourth International Conference On Information Integration and Web-based Applications & Services, Bandung (Indonesia), http://iiwas.comp.nus.edu.sg/
16.09.-18.09.	**SAICSIT 2002:** Enablement through Technology, Port Elizabeth (South Africa), http://www.petech.ac.za/saicsit2002
19.09.-21.09.	**PDCS'02:** 15th International Conference on Parallel and Distributed Computing Systems, Louisville KY (USA), http://www.isca-hq.org/PDCS-2002-call.htm
23.09.-26.09.	**CLUSTER '02:** IEEE Fourth International Conference on Cluster Computing, Chicago IL (USA), http://www-unix.mcs.anl.gov/cluster2002/
26.09.-28.09.	**ACI '02:** The IASTED International Conference on Artificial Computational Intelligence, Tokyo (Japan), http://www.iasted.org/conferences/2002/japan/c365.htm
30.09.-02.10.	**CVE '02:** Collaborative Virtual Environments, Bonn (Germany), http://web.mit.edu/tps/NL/SIGDOC_WWW/sigdoc2002/cfp.htm
01.10.-04.10.	**ISC '02:** The IASTED International Conference on Intelligent Systems and Control, Tsukuba (Japan), http://www.iasted.org/conferences/2002/japan/isc.htm>
01.10.-03.10.	**InfraSec '02:** Infrastructure Security Conference 2002, Bristol (United Kingdom), http://www.infrasec-conf.org/

Buch-Tipp



Telematik NetzModerneNavigatoren, hsg. Jeannot Simmen, 112 Seiten, **Euro 20.—,** Verlags-Buchhandlung König, Köln (ISBN 3-88375-547-8), Kontakt: simmen@snafu.de

Telematik bildet heute das Leitmedium der IT-Branche. Nach Multimedia und Interaktivität zeigt Telematik als Schlüssel-Technologie den dritten Innovationsschub. Tele(infor)matik erscheint als innovative und zauberhafte, automatische «Wirkung auf Distanz».

Die Neuerscheinung **«Telematik - NetzModerneNavigatoren»** veranschaulicht die Fernwirkung als das moderne Kulturmodell der Netz-Gesellschaft. Aktuelle Essays und Basis-Texte beleuchten umfassend die Geschichte der Telematik von Götter-Strahlen ins utopische Übermorgen.

Das farbig-gedruckte Buch umfasst 15 Essays, 40 Design-Entwürfe, 112 S. und rund 100 Abbildungen. Bildfolgen von Yves Netzhammer, Urs Lüthy, Thomas Ruff, Carlo Crivelli und Michelangelo.

Er erschien anlässlich der Preis-Verleihung vom Ideen-Wettbewerb «Telematik», ausgeschrieben vom Fachbereich Design der Universität Essen, in Kooperation mit Studiengang Architektur der Universität der Künste, Berlin. Der Wettbewerb wird zukünftig als «Deutscher Telematik Award» stattfinden, ausgelobt von «Telematics Pro e.V.».

Teil I: Neue Texte von Peter Weibel, Norbert Bolz, Jeannot Simmen, Oliver Grau, Christoph Asendorf und Andres Janser beschreiben die Fernwirkung in Science-Fiction, Medien, Kunst, Architektur, Literatur und Film.
Teil II: Die Gewinner, Anerkennungen und alle Beiträge vom ersten «Telematik-Wettbewerb», eine Initiative vom FB Design der Uni Essen.
Teil III: Basis-Texte: Paul Valéry, Vilém Flusser, Eduardo Kac, Erich Kästner und Wolf-Dieter Klemt - Die Telematik-Avantgarde antizipiert moderne, automatisch ablaufende Fernprozesse. ■

TELEMATIK Autorenhinweise

Die Zeitschrift TELEMATIK begrüßt wissenschaftliche, technische, wirtschaftliche oder soziale Beiträge, die aus dem Bereich der Telematik stammen. Zur Veröffentlichung in TELEMATIK können Fachartikel, Berichte und Leserbriefe in Deutsch oder Englisch angenommen werden. Das Thema des Fachartikels soll in anwendungsnaher Form behandelt sein, welches einer breiten Leserschaft und nicht nur wenigen Experten verständlich ist. Berichte über Veranstaltungen, Messen, Berufsentwicklungen o.ä. sollen ebenfalls für eine breite Leserschaft interessant sein.

Gliederung
Wir ersuchen Sie bei Fachartikeln folgende Gliederung zu berücksichtigen:
(1) In der Einleitung sollen der Hintergrund, Auswirkung und Ziel der Arbeit für ein breites Publikum,
(2) im Hauptteil die fachliche Komponente der Arbeit (inklusive dem Stand der Technik) und
(3) in der Zusammenfassung prägnante Schlussfolgerungen und Auswirkungen
beschrieben werden. Der Text ist in Abschnitte und ggf. in Unterabschnitte mit Überschriften zu unterteilen.

Titel, Kurzfassung und Schlüsselwörter
Der Titel des Fachartikels soll möglichst kurz und aussagekräftig gewählt werden. Eine Kurzfassung (ca. 50 Worte) sowie Schlüsselwörter (max. 5) sollen am Beginn des Textes eingefügt werden.

Abbildungen und Tabellen
Abbildungen und Tabellen werden durchlaufend nummeriert und im Text referenziert werden. Bild- bzw. Tabellenunterschriften sollen zur näheren Beschreibung verwendet werden.

Literaturangaben
Literaturhinweise sind im Text mit fortlaufenden Nummern in eckigen Klammern zu bezeichnen und am Ende des Textes unter der Überschrift "Literatur" einzeln nummeriert in folgender Weise anzufügen:

Die Literaturhinweise müssen folgende Angaben beinhalten: (a) bei Büchern: Namen aller Autoren, Buchtitel, Verlag, Verlagsort, Erscheinungsjahr und ggf. Seiten- oder Kapitelangaben; (b) bei Journalen: Namen aller Autoren, Titel, Journaltitel, Band und Lieferungsnummer, Erscheinungsjahr, Seitennummern.
Beispiele:

[1] J. P. Hayes, „Computer Architecture and Organization," (3rd ed.), McGraw-Hill, 1998.
[2] L. Watson and J. Gurd, „A Practical Dataflow Computer," IEEE Computer, Vol. 15, No. 2, Feb. 1982, pp. 51-57.
[3] M. Easley and E. Bradley, „Generalized Physical Networks for Automated Model Building," Proc. Intern. Joint Conf. on Artificial Intelligence, Stockholm, Sweden, 1999, pp. 1047-1052.

Kontaktinformation der Autoren
Am Ende des Fachbeitrages werden Kontaktinformationen der Autoren (Position, Anschrift, Email) abgedruckt.

Einsendung
Senden Sie bitte Ihr Manuskript sowohl auf Papier als auch in elektronischer Form in einem deutlich definierten Format (bevorzugt MS-Word) auf Diskette oder per Email an die unten angeführte Adresse. Bilder, Tabellen und Grafiken sollten in eigenen Dateien (JPG, TIF oder EPS-Format) abgespeichert werden und nicht in den Text eingebunden sein, sondern die von Ihnen gewünschte Positionierung mit einem Hinweis, z.B. "hier Abb.1", angezeigt werden.

Wir editieren Ihren Beitrag, um eventuell eine notwendige Kürzung zu erreichen oder ein gewisses Format einzuhalten.

TIV – Telematik Ingenieur Verband
Inffeldgasse 16b, A-8010 Graz
Tel.: 0316/873-6403, FAX: 0316/873-6903
e-mail: redaktion@tiv.tu-graz.ac.at

Architecture as Information Editor

Manfred Wolff-Plottegg
Institut für Gebäudelehre und Entwerfen,
Technische Universität Wien

When I claim I have done something with my „little finger" (with no effort at all), this is, as usual, a slight exaggeration; however, there are people („*The Belly of an Architect*") who say they act on a gut level – because for them that is where a whole lot of nerves converge – while others again claim that it comes from the brain; and today many things are ascribed to the computer. Where the processing actually takes place was perhaps once an issue of location (traditionally the *genius loci*), but with growing experience of dislocation, we might now, in retrospect, have to admit that topographical differences cannot really be evidenced by way of autochthonous results. But the questions remain: how do lines get drawn on paper and how do houses appear in the field?

Architecture information processing I

A client approached me, stating that she wanted a house for her retirement, with a roof and a balcony (something between Salzburg and Tyrolean style), a dream house, illustrated by a stack of (holiday and souvenir) photos, and a few „Homes & Gardens" books: so there was the English fireplace, the French window, the terrace like the one on holiday in Greece, of course Italian terracotta and heavy Spanish wood, a touch of Biedermeier, but also with windows for flowers and a bit of „bio" and „eco" too – an architectural picture puzzle. There is no point in collecting information if the rules of processing are unknown.[1]

All „own home-builder" houses follow a self-similar basic pattern. Although a person's own individual desire is asserted – *all you need is love...* – the self-similarity manifests a microcensus, a favourite collective train of thought: the precedented, the liking, ... If the result is a copy of the desire, i.e. if it is already known: what is „information processing" if nothing is processed? analogue or digital? > merge, morph, copy/paste; > as in the SIRD[2] mode of seeing the familiar pattern catches the eye.

Architecture information processing II

Classical architectural theory is based upon information processing. And yet in competitions (with, for example, 100 projects) quite different solutions may be found and, if we supply even more information, the results do not become distinctively different. One might say that this is not serious information processing.[3] In the case of the own home-builder, we see an example of how conventional sources and manipulations are obsolete: only beginners analyse a site or a set of parameters for designing, only romantics and information scientists confide themselves to their architect in this way and believe that architecture is an information apparatus.[4]

If we are no longer useful in a world without a subject / object, if we are aimless, desireless and placeless, information floats without obligation. The *Binary House*[5] is architecture production in that it produces information for interpretations, manipulation of information as a generator of architecture.

Architecture information processing III

In view of the fact that it was only possible to achieve little deviation and only insufficient results with the anthropocentric goal- and content-focused approach the question is whether external, collective procedure could perhaps help create any kind of new results. Not the input (individual desire), but the process determines the output. The information flow does not go from the brain (vision, desire....) to expression (extremity, medium). External processes generate and offer new information to the brain. W. A. Mozart (KV 516f „Musical Dice Game"), A. Cozens (A new method of assisting the invention in drawing original compositions of landscape, 1785): *„To sketch ... is to transfer ideas from the mind to the paper ... to blot is to make varied spots ... producing accidental forms ...from which ideas are presented to the mind ...; To sketch is to delineate ideas; blotting suggests them."* Without historical, evaluative admixture

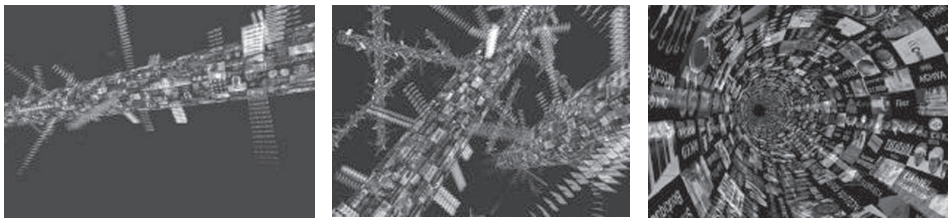


Fig.1: *Infotube (Matsumoto/Matsukawa/Wakita) ..... Information Spaces*

1 This contract was short-lived, the client employed another architect to process her input.

2 single image random dot

3 And from the sum of similarities or differences we cannot draw any reliable conclusions as to the common defaults. Architecture bluffs with the reliability and stringency of information processing.

4 Managers generally believe that architecture is the result of decisions.

5 Project and theory: Plottegg already in 1988

we gain surprise and speed. The ease of process control outdoes the procedure of analysis. Fuzzy simulations as antitheses of „correct" „thought processing", the Internet as non-goal-focused, collective information generator. The art of design is to plan something unknown and not to determine it but to leave it unknown.

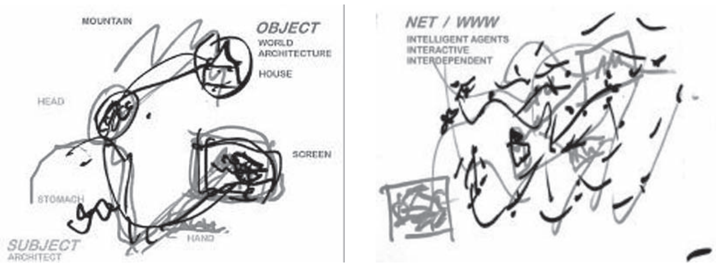


Fig.2: *„the planning architect"* >>>> *„The Binary House"*

Architecture information processing IV

The Neuronal Architecture Processor[6] - an installation consisting of two digital processors that communicate with each other, the output of each being projected by a beamer – is based on the idea that a sequence of pulses (spike trains) in biological organisms = equals = binary streams of signs (bit strings) = equals = data (coordinates, vectors) interpreted as geometric bodies (solids).

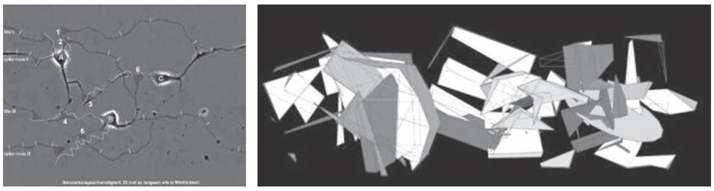


Fig.3: ...

This equation brings together three spheres of reality that are traditionally considered as distinct:
- the world in our head: information, imagination and ideas in the way they are actually coded in our brain - the world of digital data processing, represented by binary streams of signs as communication vocabulary between digital processors - the world of generating new images / spaces / architecture. These three spheres of reality are brought together under the common denominator of information processing. Thus the installation demonstrates that the generation of images / spaces / architecture must no longer be perceived as anthropocentric / expressionistic. Through the use of the computer it is possible to emancipate oneself from established patterns of behaviour, evaluation and production.

Despite the relatively low degree of complexity of this Neuronal Architecture Processor prototype, the results are more differentiated than those arising out of a traditional analogue architectural production (under the same base conditions). This has consequences for our understanding of art, architecture and human versus machine/ digital creativity: it proves our thesis that creativity (in this case production of architectural images) is the result of a „neuronal processor" and as such can be freed from the brain.

Architecture information processing V

If architecture wishes to be regarded as a creative process (design process) and as innovative information processing, the condition is that it should first abandon the procedure of visual, object-based need-responsive architecture mutating into a design oriented process, an architecture of process. Hereby, the subject (planner / user) and the object (architecture) disappear as categories. McLuhan (*The Medium is the Message*) already identified the change in the system of information carrier and information, and this development is heightened by the WWW.

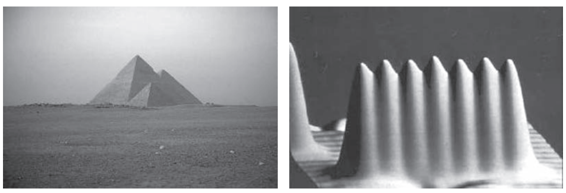


Fig.4: *we are 3 pyramids* *I am a bit*

Even urban design today is forced to focus on process control today, architecture is no longer a building or an object, urbanism is no longer function but an organ instead. We can specifically promote the aspect of architecture as a medium (very slow) and as a process, by producing an architecture of acceleration. It becomes clear, then, that this advanced architecture has relatively little to do with personal liking (harmonised with one's gut and brain), but rather with „external" processes and more global system variables: product > tool > tool machine > program > program control > system control. After cause & effect, co-determination and interaction, basics, paradigms, subsystems, system changes, system planning, open systems, after linearity, control circuits, tree structures, fractals and chaos, now self-generating systems are at hand, above and beyond process control, an architecture of avatars, the vision of autocatalytic components.

Architecture information processing VI

If architecture exists beyond sequential function derivates, and if designing is no longer methodical (systematic procedure that produces – in a finite number of steps – the answer to a question or the solution of a problem), but acts out autocatalytically, why, then, should we take the brain as a pattern for artificial creations? perhaps the gut is better, after all? or our little finger? or skin? or indeed an infinitely long bit string that is constantly generating itself 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 1 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 1 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 1 1 0 1 1 1 0 0 1 0 0 1 0 0 1 0 0 0 1 1 0 0 0 0 0 0 0 0 0 1 0 0 1 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 ... i.e., not processing something else, after analogue / anthropocentric limitations, after formalisation (styles of architecture), after the limit of algorithms[7], all „dream home" clients now become part of a 3D metalanguage. Seen in this way, architecture is no longer a medium, architecture is an information editor. Architectural design programs the editor.

PS.: Information architecture processing VII

Traditional architecture, of course, gave information, it was a carrier of meaning: *I am a church, I am power, I am a sign, ...*[8]

Today there is so much information that buildings disappear (as in the jungle of Borobudur), forms

6 Neuronal Architecture Processor by Manfred Wolff-Plottegg & Wolfgang Maass; Prototype 1999 for the exhibition „Real Virtualities" Künstlerhaus Wien and update 2000 in „Plottegg´s Plots" Neue Galerie Graz; programming: Harry Burgsteiner / Andreas Gruber (Graz University of Technology)

7 M. Plottegg (Architektur Algorithmen 1996;The recipe for recipes, 1998)

8 cf: Venturi Learning from Las Vegas


Fig.5: *NY / Times Square*

and functions vanish, architecture is reduced to a framework for surfaces (user interfaces, information interfaces). The paradigms have changed: here, information processes architecture, information determines procedures: acceleration of architecture. ■

Prof. Dipl. Ing. Manfred Wolff-Plottegg, architect and theoretician, Head of the Institut für Gebäudelehre und Entwerfen at the Technische Universität Wien.
Homepage: http://www.gbl.tuwien.ac.at

SIGMM
Special Interest
Group
on Multimedia

ACM MultiMedia 2002
Juan Les Pins, France
December 1-6, 2002

The ACM SIGPLAN/SIGSOFT Conference on
Generators and Components (GCSE/SAIG'02)

A joint event of GCSE and SAIG, and part of PLI'02,
Pittsburgh, PA, October 6-8, 2002.

Invited Speakers:	*Neil Jones*	*Catuscia Palamidessi*	*Janos Sztipanovits*
	University of Denmark	Penn State University	Vanderbilt University

Program generation has the prospect of being an integral part of a wide range of software development processes. Many recent studies investigate different aspects of program generation, including their semantics, their application, and their implementation. Existing theories and systems address both high-level (source) language and low-level (machine) language generation. A number of programming languages now support program generation and manipulation, with different goals, implementation techniques, and applications. The goal of this conference is to provide a meeting place for researchers and practitioners interested in this topic. A particular area of interest is component-based software development, which bears the promise of considerable productivity increases to software development comparable to the introduction of the assembly line in manufacturing. But due to the very same sophistication that makes components useful, their maintenance can be hard. Generative programming presents a promising approach to alleviating the above problems, as changes affecting components can now be more effectively managed during the generation process rather than at the component level. The goal of this joint event is to foster further cross-fertilization between the software engineering research community on the one hand, and the programming languages community on the other, in addition to supporting the original research goals of both GCSE and SAIG communities.

Architektur als Informations-Editor

Manfred Wolff-Plottegg
Institut für Gebäudelehre und Entwerfen,
Technische Universität Wien

Wenn ich behaupte, ich hätte etwas mit dem kleinen Finger (oder „mit links“) gemacht, ist das, wie üblich, ein Understatement; es gibt aber auch Leute (*„Der Bauch des Architekten“*), die sagen, sie machen etwas aus dem Bauch - weil sie dort sehr viele Nerven zusammenlaufen hätten -, während andere hirnlastig behaupten, es komme aus dem Kopf; und derzeit wird vieles dem Computer zugeordnet. Wo nun die Prozessoren sind, war früher eventuell ein Thema der Location (traditionell genius loci), mit der Erfahrung der Dislokation könnten wir nun rückblickend meinen, dass sich topografische Unterschiede zumeist nicht wirklich per autochtonen Ergebnissen nachweisen lassen. Aber es bleiben die Fragen: Wie kommen die Striche aufs Papier und wie kommen die Häuser auf die Wiese?

Architektur Informationsverarbeitung I

Eine Klientin kam zu mir, sie wollte ein Haus für den Rückzug im Alter, mit Dach und Balkon (so zwischen salzburgisch und tirolerisch), ein Haus nach Wunsch, belegt durch einen Stapel von (Urlaubs- und Erinnerungs-) Fotos, einige „schöner Wohnen“-Bücher: also der englische Kamin, das französische Fenster, die Terrasse wie damals auf Urlaub in Griechenland, natürlich italienisches Terrakotta und spanisch schweres Holz, ein wenig Biedermeier, aber schon mit Blumenfenster und auch etwas Bio & Öko sollte dabei sein - ein architektonisches Bilderpuzzle. Es ist sinnlos Informationen zu sammeln, wenn die Regeln der Verarbeitung nicht bekannt sind.[1]

Alle Häuser der Häuslbauer sind ein selbstähnliches Limesbild. Obwohl jeweils genau das eigene individuelle Wunschbild - *all you need is love....* - behauptet wird, manifestiert sich in der Selbstähnlichkeit ein Microzensus, ein kollektiver Favoriten-Gedankengang: das schon Dagewesene, der Gefallen, ... Wenn das Ergebnis eine Kopie des Wunschbildes ist, wenn es also ohnehin schon bekannt ist: worin besteht „Informationsverarbeitung“, wenn nichts verarbeitet wird? analog oder digital? > merge, morph, copy/paste; > wie bei den SIRD-Sehweisen[2] springt das Limesbild ins Auge.

Architektur Informationsverarbeitung II

Die klassische Architekturlehre geht von der Verarbeitung von Informationen aus. Dennoch sind bei Wettbewerben (mit z.B. 100 Projekten) durchaus verschiedene Lösungen zu finden und gibt man noch weitere Informationen dazu, werden die Ergebnisse nicht markant anders. Man könnte sagen, hier werden Informationen nicht seriös verarbeitet.[3] Beim Häuslbauer sehen wir exemplarisch, wie herkömmliche Quellen und Manipulationen obsolet sind: Nur Anfänger analysieren ein Grundstück oder Bedürfnisse als Planungsparameter, nur Romantiker und Informatiker vermitteln sich ihrem Architekten, glauben Architektur sei ein Informationsverarbeitungsapparat.[4]

Wenn wir in einer Welt ohne Subjekt /Objekt uns selbst nicht mehr brauchen, ziel-, wunschbild- und grundstückslos sind, flottieren Informationen unverbindlich. Das *Binäre Haus*[5] ist insofern Architekturproduktion, als es Informationen für Interpretationen produziert: Informationsmanipulation als Architekturgenerator.

Architektur Informationsverarbeitung III

Da bisher mit der anthropozentrischen, zielorientierten, inhaltlichen Vorgangsweise eigentlich nur wenig Abweichendes, nur mangelhafte Ergebnisse erzielbar waren, stellt sich die Frage, ob nicht externe, kollektive Handlungsanweisungen x-beliebig neuere Ergebnisse hervorbringen könnten. Nicht der Input (individuelles Wollen), sondern das Prozedere bestimmen den Output. Der Informationsfluss geht nicht vom Hirn (Vision, Wunschbild ...) zur Äußerung (Extremität, Medium). Externe Vorgänge generieren und bieten dem Hirn neue Information: W. A. Mozart (KV 516f „Musikalisches Würfelspiel“), A. Cozens („A new method of assisting the invention in drawing original compositions of landscapes“, 1785): *„To sketch ... is to transfer ideas from the mind to the paper ... to blot is to make varied spots ... producing accidential forms ... from which ideas are presented to the mind ...; To sketch is to delineate ideas; blotting suggests them“*. Ohne historische, wertende Einmengungen gewinnen wir an Überraschung, an Geschwindigkeit, die Leichtigkeit der Prozesssteuerung überbietet die Prozedur der Analyse. Fuzzy Simulationen als Antithesen einer „richtigen“ „Gedankensteuerung“, das Internet als nicht-zielorientierter, kollektiver Informationsgenerator. Die Kunst des Planens ist, etwas Unbekanntes zu planen und dies unbekannt zu lassen, nicht zu determinieren.

Architektur Informationsverarbeitung IV

Der Neuronale Architektur Generator[6] - eine Installation bestehend aus zwei miteinander kom

1 Dieser Auftrag fand ein schnelles Ende, die Klientin nahm sich zur Verarbeitung ihres Inputs einen anderen Architekten.

2 single image random dot

3 Und aus der Summe der Gleichheiten bzw. Unterschiedlichkeiten lassen sich keine verlässlichen Schlüsse auf die gemeinsamen Vorgaben ziehen. Architektur blufft mit der Verlässlichkeit und Stringenz der Informationsverarbeitung.

4 Manager glauben zumeist, Architektur sei das Ergebnis von Entscheidungen.

5 Projekt und Theorie: Plottegg schon 1988

munizierenden digitalen Prozessoren, deren Output projiziert wird - geht davon aus, dass Pulsfolgen (spike trains) in biologischen Organismen gleich = binäre Zeichenreihen (bit strings) gleich = Daten (Koordinaten, Vektoren) interpretierbar als geometrische Volumen (solids) sind. Diese Gleichung verknüpft drei traditionell als wesensfremd angesehene Wirklichkeitsbereiche: die Welt in unserem Kopf: Informationen, Vorstellungen und Ideen wie sie in biologischen Organismen tatsächlich kodiert sind; die Welt der digitalen Datenverarbeitung, repräsentiert durch binäre Zeichenreihen als Vokabular der Kommunikation zwischen digitalen Prozessoren; die Welt der Generierung neuer Bilder / Räume / Architekturen. Diese drei Wirklichkeitsbereiche werden hier auf dem gemeinsamen Nenner der Informationsverarbeitung miteinander verknüpft. Die Installation demonstriert auf diese Weise, dass die Generierung von Bildern/Räumen/Architekturen nicht mehr anthropozentrisch/expressionistisch gesehen werden muss. Durch die Computeranwendung wird sozusagen ein Schritt der Emanzipation von althergebrachten Verhaltens-, Evaluations- und Produktionsmustern ermöglicht.

Trotz der vergleichsweise geringen Komplexität des Prototyps des Neuronalen Architektur Prozessors erscheinen die daraus gewonnenen Outputs differenzierter als die der bisherigen analogen Architektur-Produktion (bei gleichen Randbedingungen). Dies hat Konsequenzen für unsere Auffassung von Kunst, Architektur und menschlicher bzw. maschinell/digitaler Kreativität: es beweist unsere These, dass die Kreativität (hier Produktion von Architekturbildern) ein Produkt eines „neuronalen Prozessors“ ist und als solche durchaus vom „Hirn“ losgelöst werden kann.

Architektur Informationsverarbeitung V

Will sich Architektur als kreativer Vorgang (Planungsprozess) und innovative Informationsverarbeitung verstanden wissen, ist Vorbedingung, dass sie vom Prozedere der bildhaften, objekthaften, Bedürfnisbefriedigungs-Architektur absieht und zu einer prozessorientierten Planung, zu einer prozesshaften Architektur mutiert. Dabei verschwinden Subjekt (Planer/Nutzer) und Objekt (Architektur) als Kategorien.

6 „Neuronaler Architektur Prozessor“ von Manfred Wolff-Plottegg & Wolfgang Maass; Prototype 1999 für die Ausstellung „Real Virtualities“ Künstlerhaus Wien und Update 2000 in „Plottegg´s Plots“ Neue Galerie Graz; Programmierung: Harry Burgsteiner / Andreas Gruber (Technische Universität Graz)

Schon McLuhan (*The Medium is the Message*) hat den Wandel im System von Informationsträger und Information referenziert, und die Entwicklung hat sich im WWW noch verschärft.

Auch der Städtebau beschäftigt sich heute gezwungenermaßen mit Prozesssteuerung, Architektur ist nicht mehr Gebäude oder Objekt, Urbanismus nicht Funktion sondern Organ. Wir können gezielt den Aspekt Architektur als Medium (sehr langsam) und als Prozess forcieren, und eine Architektur der Beschleunigung betreiben. Somit wird klar, dass diese avancierte Architektur relativ wenig mit dem persönlichem Gefallen (abgestimmt mit Bauch und Hirn) zu tun hat, viel eher mit „externen“ Abläufen und globaleren Systemvariablen: Produkt > Werkzeug > Werkzeugmaschine > Programm > Programmsteuerung > Systemsteuerung ... Nach Ursache & Wirkung, Mitbestimmung und Interaktion, Grundlagen, Paradigmen, Teilsystemen, Systemveränderungen, Systemplanung, offenen Systemen, nach Linearität, Regelkreisen, Baumstrukturen, Fraktalen, Chaos sind nun selbstgenerierende Systeme zur Disposition, über Prozesssteuerung hinaus, eine Architektur der Avatare, die Vision von autokatalytischen Bauteilung.

Architektur Informationsverarbeitung VI

Wenn es Architektur auch jenseits von sequenziellen Architektur-Funktions-Derivaten gibt, Planung nicht mehr methodisch (systematic procedure that produces - in a finite number of steps - the answer to a question or the solution of a problem), sondern autokatalytisch agiert, warum also Hirn als Muster für artifizielle Kreationen nehmen? Vielleicht doch besser Bauch?, oder kleiner Finger? oder Haut? oder eben ein unendlich langer bit-string der sich ständig selbst generiert 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 1 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 1 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 1 1 0 1 1 1 0 0 1 0 0 1 0 0 1 0 0 0 1 1 0 0 0 0 0 0 0 0 0 1 0 0 1 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 ... also nicht etwas anderes verarbeitet, also nach der analogen/anthropozentrischen Beschränktheit, nach der Formalisierung (Architektur-Stile), nach dem

7 M. Plottegg („Architektur Algorithmen“ 1996; Das Rezept für Rezepte, 1998)

Limes der Algorithmen[7], alle „Wunschhaus“-Klienten werden nun Teil einer 3D-Metasprache. So gesehen ist Architektur nicht mehr ein Medium, Architektur ist ein Editor. Architekturplanung programmiert den Editor.

PS.: Information Architekturverarbeitung VII

Traditionelle Architektur gab natürlich Informationen, war Bedeutungsträger: *ich bin eine Kirche, ich bin Macht, ich bin Zeichen, ...*[8]

Nun gibt es soviel Information, dass die Gebäude verschwinden (wie im Urwald von Borobudur), Formen und Funktionen verschwinden, Architektur reduziert sich zum Gerüst für Oberflächen (Benutzeroberflächen, Informationsoberflächen). Die Fronten sind gewechselt: hier verarbeitet die Information die Architektur, Informationen bestimmen die Handlungsweisen: Beschleunigung der Architektur. ■

8 siehe hiezu auch: Robert Venturi „Learning from Las Vegas“

Publications of the Institut für Grundlagen der Informationsverarbeitung 1992-2002

Popular Science Articles

W. Maass. wetware (English version). In *TAKEOVER: Who is Doing the Art of Tomorrow (Ars Electronica 2001)*, pages 148-152. Springer, 2001.

W. Maass. wetware (deutsche Version). In *TAKEOVER: Who is Doing the Art of Tomorrow (Ars Electronica 2001)*, pages 153-157. Springer, 2001.

W. Maass. Neural computation: a research topic for theoretical computer science? Some thoughts and pointers. In Rozenberg G., Salomaa A., and Paun G., editors, *Current Trends in Theoretical Computer Science, Entering the 21th Century*, pages 680-690. World Scientific Publishing, 2001.

W. Maass. Neural computation: a research topic for theoretical computer science? Some thoughts and pointers. In *Bulletin of the European Association for Theoretical Computer Science (EATCS)*, volume 72, pages 149-158, 2000.

W. Maass, A. Pinz, R. Braunstingl, G. Wiesspeiner, T. Natschläger, O. Friedl, and H.M. Burgsteiner. Konstruktion von Lernfähigen Robotern im Studentenwettbewerb „Robotik 2000'' an der Technischen Universität Graz. in: *Telematik*, pages 20-24, 2000.

W. Maass. Spike trains - im Rhythmus neuronaler Zellen. In R. Kriesche H. Konrad, editor, *Katalog der steirischen Landesausstellung gr2000az*, pages 36-42. Springer Verlag, 2000.

W. Maass. Lernende Maschinen. In R. Kriesche H. Konrad, editor, *Katalog der steirischen Landesausstellung gr2000az*, pages 50-56. Springer Verlag, 2000.

W. Maass. Das menschliche Gehirn – nur ein Rechner?. In R. E. Burkard, W. Maass, and P. Weibel, editors, *Zur Kunst des Formalen Denkens*, pages 209-233. Passagen Verlag (Wien), 2000.

W. Maass and P. Weibel. Ist die Vertreibung der Vernunft reversibel? Überlegungen zu einem Wissenschafts- und Medienzentrum. In P. Weibel, editor, *Jenseits von Kunst*, pages 745-747. Passagen Verlag, 1997.

Scientific Articles

2002

O. Aichholzer, L.S. Alboul, and F. Hurtado. On flips in polyhedral surfaces. to appear in *International Journal of Foundations of Computer Science (IJFCS),* special issue on Volume and Surface Triangulations, 2002.

O. Aichholzer, F. Aurenhammer, and F. Hurtado. Sequences of spanning trees and a fixed tree theorem. Computational Geometry: *Theory and Applications*, 21(1-2):3-20, 2002. Special Issue.

O. Aichholzer, F. Aurenhammer, and H. Krasser. On the crossing number of complete graphs. In *Proc. 18th European Workshop on Computational Geometry CG* '02 Warszawa, Warszawa, Poland, 2002.

O. Aichholzer, F. Aurenhammer, and H. Krasser. Progress on rectilinear crossing numbers. *Technical report*, IGI-TU Graz, Austria, 2002.

O. Aichholzer, F. Aurenhammer, and B. Palop. Quickest paths, straight skeletons, and the city Voronoi diagram. submitted for publication, 2002.

P. Auer, N. Cesa-Bianchi, and P. Fischer. Finite time analysis of the multiarmed bandit problem. *Machine Learning*, 47(2/3):235-256, 2002. A preliminary version has appeared in *Proc. of the 15th International Conference on Machine Learning*.

P. L. Bartlett, W. Maass. Vapnik-Chervonenkis dimension of neural nets. *Handbook of Brain Theory and Neural Networks*, 2nd ed., MIT Press, 2002.

S. Häusler, W. Maass, and H. Markram. Low dimensional readout from high dimensional neural circuits. submitted for publication, 2002.

R. A. Legenstein and W. Maass. Neural circuits for pattern recognition with small total wire length. *Theoretical Computer Science*, 2002, in press.

R. A. Legenstein, W. Maass, and H. Markram. Input prediction and autonomous movement analysis in recurrent circuits of spiking neurons. submitted for publication, 2002.

W. Maass. Computation with spiking neurons. *Handbook of Brain Theory and Neural Networks*, 2nd ed., MIT Press, 2002.

W. Maass and H. Markram. Temporal integration in recurrent microcircuits. *Handbook of Brain Theory and Neural Networks*, 2nd ed., MIT Press, 2002.

W. Maass and H. Markram. On the computational power of recurrent circuits of spiking neurons. submitted for publication, 2002.

W. Maass and H. Markram. Synapses as dynamic memory buffers. *Neural Networks*, 2002. in press.

W. Maass, G. Steinbauer, and R. Koholka. Autonomous fast learning in a mobile robot. Springer Lecture Notes in Computer Science, 2002, in press. ©Springer-Verlag. See http://www.springer.de/comp/lncs/index.html.

H. Markram, M. Ofer, T. Natschläger, and W. Maass. Liquid computing. submitted for publication, 2002.

T. Natschläger and W. Maass. Spiking neurons and the induction of finite state machines. *Theoretical Computer Science: Special Issue on Natural Computing*, 2002, in press.

A. Schwaighofer, V. Tresp, P. Mayer, A. K. Scheel, M. Reuss-Borst, A. Krause, I. Meseckevon Rheinbaben, and H. Rost. Prediction of rheumatoid joint inflammation based on laser imaging using linear and kernel-based classifiers. *IEEE Transactions on Biomedical Engineering*, 2002. Submitted.

2001

O. Aichholzer, L.S. Alboul, and F. Hurtado. On flips in polyhedral surfaces. In *Proc. 17th European Workshop on Computational Geometry CG ,2001*, pages 27-30, Berlin, Germany, 2001.

O. Aichholzer, F. Aurenhammer, B. Brandtstätter, H. Krasser, C. Magele, M. Mühlmann, and W. Renhart. Evolution strategy and hierarchical clustering. In *13th COMPUMAG Conference on the Computation of Electromagnetic Fields*, Lyon-Evian, France, 2001.

O. Aichholzer, F. Aurenhammer, F. Hurtado, and H. Krasser. Towards compatible triangulations. In Jie Wang, editor, *Proc. 7th Ann. Int'l. Computing and Combinatorics Conf. COCOON'01*, Lecture Notes in Computer Science, volume 2108, pages 101-110, Guilin, China, 2001. Springer Verlag.

O. Aichholzer, F. Aurenhammer, F. Hurtado, and H. Krasser. Towards compatible triangulations. *Theoretical Computer Science*, 2001. Special Issue, invited.

O. Aichholzer, F. Aurenhammer, C. Icking, R. Klein, E. Langetepe, and G. Rote. Generalized self-approaching curves. *Discrete Applied Mathematics*, 109(1-2):3-24, 2001. Special Issue.

O. Aichholzer, F. Aurenhammer, and H. Krasser. On compatible triangulations of point sets. In Proc. *17th European Workshop on Computational Geometry CG ,2001,* pages 23-26, Berlin, Germany, 2001.

O. Aichholzer, F. Aurenhammer, and H. Krasser. Enumerating order types for small point sets with applications. In *Proc. 17th Ann. ACM Symp. Computational Geometry*, pages 11-18, Medford, Massachusetts, USA, 2001.

O. Aichholzer, D. Bremner, E.D. Demaine, D. Meijer, V. Sacristán, and M. Soss. Long proteins with unique optimal foldings in the h-p model. In *Proc. 17th European Workshop on Computational Geometry CG ,2001*, pages 59-62, Berlin, Germany, 2001.

O. Aichholzer, C. Cortés, E.D. Demaine, V. Dujmovic, J. Erickson, H. Meijer, M. Overmars, B. Palop, S. Ramaswami, and G.T. Toussaint. Flipturning polygons. *DCG, 2001*. to appear.

O. Aichholzer, E.D. Demaine, J. Erickson, F. Hurtado, M. Overmars, M.A. Soss, and G.T. Toussaint. *Reconfiguring convex polygons. Computational Geometry: Theory and Applications,* 20:85-95, 2001.

O. Aichholzer, F. Hurtado, and M. Noy. On the number of triangulations every planar point set must have. In *Proc. 13th Annual Canadian Conference on Computational Geometry CCCG 2001*, pages 13-16, Waterloo, Ontario, Canada, 2001.

O. Aichholzer and H. Krasser. The point set order type data base: A collection of applications and results. In *Proc. 13th Annual Canadian Conference on Computational Geometry CCCG 2001*, pages 17-20, Waterloo, Ontario, Canada, 2001.

P. Auer, H. M. Burgsteiner, and W. Maass. Universal learning with parallel perceptrons. submitted for publication, 2001.

P. Auer, H.M. Burgsteiner, and W. Maass. The p-delta learning rule for parallel perceptrons. submitted for publication, 2001.

F. Aurenhammer. Computational geometry – some easy questions and their recent solutions. *J. Universal Computer Science*, 7:338-354, 2001. Special Issue.

F. Aurenhammer, N. Katoh, H. Kojima, M. Ohsaki, and Y.-F. Xu. Approximating uniform triangular meshes in polygons. *Theoretical Computer Science*, 2001. Special Issue, to appear.

R. A. Legenstein and W. Maass. Foundations for a circuit complexity theory of sensory processing. In Todd K. Leen, Thomas G. Dietterich, and Volker Tresp, editors, *Advances in Neural Information Processing Systems, (NIPS ,2000)*, volume 13, pages 259-265, Cambridge, 2001. MIT Press.

R. A. Legenstein and W. Maass. Optimizing the layout of a balanced tree. submitted for publication, 2001.

W. Maass. Neural computation: a research topic for theoretical computer science? Some thoughts and pointers. In Rozenberg G., Salomaa A., and Paun G., editors, *Current Trends in Theoretical Computer Science*, Entering the 21th Century, pages 680-690. World Scientific Publishing, 2001.

W. Maass. wetware (deutsche Version). In *TAKEOVER: Who is Doing the Art of Tomorrow* (Ars Electronica 2001), pages 153-157. Springer, 2001.

W. Maass. wetware (English version). In *TAKEOVER: Who is Doing the Art of Tomorrow* (Ars Electronica 2001), pages 148-152. Springer, 2001.

W. Maass. On the relevance of time in neural computation and learning. *Theoretical Computer Science*, 261:157-178, 2001.

W. Maass, T. Natschläger, and H. Markram. Real-time computing without stable states: A new framework for neural computation based on perturbations. submitted for publication, 2001.

T. Natschläger and W. Maass. Computing the optimally fitted spike train for a synapse. *Neural Computation*, 13(11):2477-2494, 2001.

T. Natschläger and W. Maass. Finding the key to a synapse. In Todd K. Leen, Thomas G. Dietterich, and Volker Tresp, editors, *Advances in Neural Information Processing Systems (NIPS ,2000),* volume 13, pages 138-144, Cambridge, 2001. MIT Press.

T. Natschläger, W. Maass, E. D. Sontag, and A. Zador. Processing of time series by neural circuits with biologically realistic synaptic dynamics. In Todd K. Leen, Thomas G. Dietterich, and Volker Tresp, editors, *Advances in Neural Information Processing Systems 2000 (NIPS ,2000)*, volume 13, pages 145-151, Cambridge, 2001. MIT Press.

T. Natschläger, W. Maass, and A. Zador. Efficient temporal processing with biologically realistic dynamic synapses. *Network: Computation in Neural Systems*, 12:75-87, 2001.

T. Natschläger, B. Ruf, and M. Schmitt. Unsupervised learning and self-organization in networks of spiking neurons. In U. Seiffert and L. C. Jain, editors, Self-Organizing *Neural Networks. Recent Advances and Applications*, volume 78 of Springer Series on Studies in Fuzziness and Soft Computing. Springer-Verlag, Heidelberg, 2001.

A. Schwaighofer and V. Tresp. The Bayesian committee support vector machine. In *Artificial Neural Networks – ICANN 2001*. Springer Verlag, 2001.

V. Tresp and A. Schwaighofer. Scalable kernel systems. In *Artificial Neural Networks – ICANN 2001*. Springer Verlag, 2001.

2000

O. Aichholzer. Extremal properties of 0/1-polytopes of dimension 5. In G. Ziegler and G. Kalai, editors, *Polytopes - Combinatorics and Computation*, pages 111-130. Birkhäuser, 2000.

O. Aichholzer, F. Aurenhammer, B. Brandtstätter, T. Ebner, H. Krasser, and C. Magele. Niching evolution strategy with cluster algorithms. In *9th Biennial IEEE Conf. Electromagnetic Field Computations*, Milwaukee, Wisconsin, USA, 2000.

O. Aichholzer, F. Aurenhammer, and F. Hurtado. Edge operations on non-crossing spanning trees. In *Proc. 16th European Workshop on Computational Geometry CG'2000*, pages 121-125, Eilat, Israel, 2000.

O. Aichholzer, C. Cortés, E.D. Demaine, V. Dujmovic, J. Erickson, H. Meijer, M. Overmars, B. Palop, S. Ramaswami, and G.T. Toussaint. Flipturning polygons. In *Proc. Japan Conference on Discrete and Computational Geometry JCDCG 2000*, Tokay University, Tokyo, Japan, 2000.

O. Aichholzer, E.D. Demaine, J. Erickson, F. Hurtado, M. Overmars, M.A. Soss, and G.T. Toussaint. Reconfiguring convex polygons. *In Proc. 12th Annual Canadian Conference on Computational Geometry CCCG 2000*, pages 17-20, Fredericton, New Brunswick, Canada, 2000.

P. Auer. Using upper confidence bounds for online learning. In *Proceedings of the 41th Annual Symposium on Foundations of Computer Science*, pages 270-293. IEEE Computer Society, 2000.

P. Auer. An improved on-line algorithm for learning linear evaluation functions. In *Proc. 13th Ann. Conf. Computational Learning Theory*, pages 118-125. Morgan Kaufmann, 2000.

P. Auer and C. Gentile. Adaptive and self-confident on-line learning algorithms. In *Proc. 13th Ann. Conf. Computational Learning Theory*, pages 107-117. Morgan Kaufmann, 2000.

F. Aurenhammer, N. Katoh, H. Kojima, M. Ohsaki, and Y.-F. Xu. Approximating uniform triangular meshes in polygons. In *Proc. 6th Ann. Intl. Computing and Combinatorics Conference*, Lecture Notes in Computer Science, volume 1558, pages 23-33, Sydney, Australia, 2000. Springer Verlag

F. Aurenhammer and R. Klein. Voronoi diagrams. In J. Sack and G. Urrutia, editors, *Handbook of Computational Geometry*, pages 201-290. Elsevier Science Publishing, 2000.

F. Aurenhammer and Y.-F.Xu. Optimal triangulations. In P.M.Pardalos C.A.Floudas, editor, *Encyclopedia of Optimization*, volume 4, pages 160-166. Kluwer Academic Publishing, 2000.

W. Maass. Spike trains – im Rhythmus neuronaler Zellen. In R. Kriesche H. Konrad, editor, *Katalog der steirischen Landesausstellung gr2000az*, pages 36-42. Springer Verlag, 2000.

W. Maass. Lernende Maschinen. In R. Kriesche H. Konrad, editor, *Katalog der steirischen Landesausstellung gr2000az*, pages 50-56. Springer Verlag, 2000.

W. Maass. Neural computation: a research topic for theoretical computer science? Some thoughts and pointers. *In Bulletin of the European Association for Theoretical Computer Science (EATCS)*, volume 72, pages 149-158, 2000.

W. Maass. Neural computation with winner-take-all as the only nonlinear operation. In Sara A. Solla, Todd K. Leen, and Klaus-Robert Müller, editors*, Advances in Information Processing Systems*, volume 12, pages 293-299. MIT Press (Cambridge), 2000.

W. Maass. Das menschliche Gehirn — nur ein Rechner?. In R. E. Burkard, W. Maass, and P. Weibel, editors, *Zur Kunst des Formalen Denkens*, pages 209-233. Passagen Verlag (Wien), 2000.

W. Maass. On the computational power of winner-take-all. *Neural Computation*, 12(11):2519-2536, 2000.

W. Maass and T. Natschläger. A model for fast analog computation based on unreliable synapses. *Neural Computation*, 12(7):1679-1704, 2000.

W. Maass, A. Pinz, R. Braunstingl, G. Wiesspeiner, T. Natschläger, O. Friedl, and H. M. Burgsteiner. Konstruktion von Lernfähigen Robotern im Studentenwettbewerb „Robotik 2000'' an der Technischen Universität Graz. in: *Telematik*, pages 20-24, 2000.

W. Maass and E. D. Sontag. Neural systems as nonlinear filters. *Neural Computation*, 12(8):1743-1772, 2000.

A. Schwaighofer. *Fingerprint matching with spectral features*. Master's thesis, Institute for Theoretical Computer Science, Graz University of Technology, Austria, May 2000.

1999

O. Aichholzer. The path of a triangulation. In *Proc. 15th Ann. ACM Symp. Computational Geometry*, pages 14-23, Miami Beach, Florida, USA, 1999.

O. Aichholzer, F. Aurenhammer, D.Z. Chen, D.T. Lee, and E. Papadopoulou. Skew Voronoi diagrams. *Int'l. Journal of Computational Geometry & Applications*, 9:235-247, 1999.

O. Aichholzer, F. Aurenhammer, and R. Hainz. New results on MWT subgraphs. *Information Processing Letters*, 69:215-219, 1999.

O. Aichholzer, F. Aurenhammer, G. Rote, and Y.-F. Xu. Constant-level greedy triangulations approximate the MWT well. *Journal of Combinatorial Optimization*, 2:361-369, 1999. [SFB-Report F003-050, TU Graz, Austria, 1995].

P. Auer, N. Cesa-Bianchi, and P. Fischer. Finite time analysis of the multiarmed bandit problem. In *IT Workshop on Decision, Estimation, Classification and Imaging*, Santa Fe, Feb 1999.

P. Auer and P. M. Long. Structural results about on-line learning models with and without queries. *Machine Learning*, 36:147-181, 1999. A preliminary version has appeared in Proceed-

ings of the 26th ACM Symposium on the Theory of Computing.

H. M. Burgsteiner. Integration of xvision and khepera. *Technical report*, Institute for Theoretical Computer Science, Graz University of Technology, 1999.

H. Krasser. *Kompatible triangulierungen ebener Punktmengen*. Master's thesis, Institute for Theoretical Computer Science, Graz University of Technology, Austria, June 1999.

W. Maass. Computing with spiking neurons. In W. Maass and C. M. Bishop, editors, *Pulsed Neural Networks*, pages 55-85. MIT Press (Cambridge), 1999.

W. Maass. Paradigms for computing with spiking neurons. In Leo van Hemmen, editor, *Models of Neural Networks*, volume 4. Springer (Berlin), to appear, 1999.

W. Maass and B. Ruf. On computation with pulses. *Information and Computation*, 148:202-218, 1999.

W. Maass and M. Schmitt. On the complexity of learning for spiking neurons with temporal coding. *Information and Computation*, 153:26-46, 1999.

W. Maass and E. Sontag. Analog neural nets with Gaussian or other common noise distribution cannot recognize arbitrary regular languages. *Neural Computation*, 11:771-782, 1999.

W. Maass and E. D. Sontag. A precise characterization of the class of languages recognized by neural nets under Gaussian and other common noise distributions. In M. S. Kearns, S. S. Solla, and D. A. Cohn, editors*, Advances in Neural Information Processing Systems*, volume 11, pages 281-287. MIT Press (Cambridge), 1999.

W. Maass and A. M. Zador. Dynamic stochastic synapses as computational units. *Neural Computation*, 11(4):903-917, 1999.

T. Natschläger. *Efficient Computation in Networks of Spiking Neurons – Simulations and Theory*. PhD thesis, Graz University of Technology, 1999.

T. Natschläger and W. Maass. Fast analog computation in networks of spiking neurons using unreliable synapses. In *ESANN'99 Proceedings of the European Symposium on Artificial Neural Networks*, pages 417-422, Bruges, Belgium, 1999.

T. Natschläger and B. Ruf. Pattern analysis with spiking neurons using delay coding. *Neurocomputing*, 26-27(1-3):463-469, 1999.

1998

O. Aichholzer. Efficient {0,1}-string searching based on pre-clustering. In *Proc. 14th European Workshop on Computational Geometry CG , 98*, pages 11-13, Barcelona, Spain, 1998. [SFB Report F003-94, TU Graz, Austria, 1996]. .

O. Aichholzer and F. Aurenhammer. Straight skeletons for general polygonal figures in the plane. In A.M. Samoilenko, editor*, Voronoi's Impact on Modern Sciences II,* volume 21, pages 7-21. Proc. Institute of Mathematics of the National Academy of Sciences of Ukraine, Kiev, Ukraine, 1998.

O. Aichholzer, F. Aurenhammer, C. Icking, R. Klein, E. Langetepe, and G. Rote. Generalized self-approaching curves. *In Proc. 14th European Workshop on Computational Geometry CG , 98*, pages 15-18, Barcelona, Spain, 1998.

O. Aichholzer, F. Aurenhammer, C. Icking, R. Klein, E. Langetepe, and G. Rote. Generalized self-approaching curves. In *Proc. 9th Int. Symp. Algorithms and Computation ISAAC'98*, Lecture Notes in Computer Science, volume 1533, pages 317-326, Taejon, Korea, 1998. Springer Verlag.

P. Auer. On learning from ambiguous information. *Periodica Polytechnica Electrical Engineering,* 42(1):115-122, 1998.

P. Auer. Some thoughts on boosting and neural networks. In L. Cromme, T. Kolb, and H. Koch, editors, *Beiträge zum 3. Cottbuser Workshop ‚Aspekte des Neuronalen Lernens' CoWAN'98*, pages 11-28, Cottbus, Germany, October 1998. Shaker Verlag. Invited paper.

P. Auer and N. Cesa-Bianchi. On-line learning with malicious noise and the closure algorithm. *Annals of Mathematics and Artificial Intelligence*, 23:83-99, 1998. A preliminary version has appeared in Lecture Notes in Artificial Intelligence 872, Springer.

P. Auer, P. M. Long, and A. Srinivasan. Approximating hyper-rectangles: Learning and pseudorandom sets. *Journal of Computer and System Sciences*, 57(3):376-388, 1998. A preliminary version has appeared in Proc. 29th Ann. Symp. Theory of Computing.

P. Auer and W. Maass. Introduction to the special issue on computational learning theory. *Algorithmica*, 22(1/2):1-2, 1998.

P. Auer and M. K. Warmuth. Tracking the best disjunction. *Machine Learning*, 32:127-150, 1998. A preliminary version has appeared in Proceedings of the 36th Annual Symposium on Foundations of Computer Science.

F. Aurenhammer, F. Hoffmann, and B. Aronov. Minkowski-type theorems and least-squares clustering. *Algorithmica*, 20:61-76, 1998.

H. M. Burgsteiner. *Neural Networks with Spiking Neurons*. Master's thesis, Graz University of Technology, November 1998.

W. Maass. On the role of time and space in neural computation. In *Proc. of the Federated Conference of CLS'98 and MFCS'98, Mathematical Foundations of Computer Science 1998*, volume 1450 of Lecture Notes in Computer Science, pages 72-83. Springer (Berlin), 1998. Invited talk.

W. Maass. A simple model for neural computation with firing rates and firing correlations. *Network: Computation in Neural Systems*, 9(3):381-397, 1998.

W. Maass. Models for fast analog computation with spiking neurons. In *Proc. of the International Conference on Neural Information Processing 1998 (ICONIP'98)* in Kytakyusyu, Japan, pages 187-188. IOS Press (Amsterdam), 1998. Invited talk at the special session on „Dynamic Brain".

W. Maass. Spiking neurons. In *Proceedings of the ICSC/IFAC Symposium on Neural Computation 1998 (NC'98)*, pages 16-20. ICSC Academic Press (Alberta), 1998. Invited talk.

W. Maass and T. Natschläger. Associative memory with networks of spiking neurons in temporal coding. In L. S. Smith and A. Hamilton, editors, *Neuromorphic Systems: Engineering Silicon from Neurobiology*, pages 21-32. World Scientific, 1998.

W. Maass and T. Natschläger. Emulation of Hopfield networks with spiking neurons in temporal coding. In J. M. Bower, editor, *Computational Neuroscience: Trends in Research*, pages 221-226. Plenum Press, 1998.

W. Maass and P. Orponen. On the effect of analog noise in discrete-time analog computations. *Neural Computation*, 10:1071-1095, 1998.

W. Maass and M. Warmuth. Efficient learning with virtual threshold gates. *Information and Computation,* 141(1):66-83, 1998.

W. Maass and A. Zador. Computing and learning with dynamic synapses. In W. Maass and C. Bishop, editors, *Pulsed Neural Networks*, pages 321-336. MIT-Press (Cambridge), 1998.

W. Maass and A. M. Zador. Dynamic stochastic synapses as computational units. In *Advances in Neural Processing Systems*, volume 10, pages 194-200. MIT Press (Cambridge), 1998.

T. Natschläger. Networks of spiking neurons: A new generation of neural network models. In *Jenseits von Kunst*. Passagen Verlag, 1998.

T. Natschläger and B. Ruf. Spatial and temporal pattern analysis via spiking neurons. *Network: Computation in Neural Systems*, 9(3):319-332, 1998.

T. Natschläger and B. Ruf. Online clustering with spiking neurons using temporal coding. In L. S. Smith and A. Hamilton, editors, *Neuromorphic Systems: Engineering Silicon from Neurobiology*, pages 33-42. World Scientific, 1998.

B. Ruf. *Computing and learning with spiking neurons – theory and simulations*. PhD thesis, TU Graz, 1998.

B. Ruf. Networks of spiking neurons can compute linear functions using action potential timing. In T. Lindblad, editor, *Proc. of the VI-Dynn 98 conference*. Spie, 1998.

B. Ruf and M. Schmitt. Self-organization of spiking neurons using action potential timing. IEEE Transactions on Neural Networks, 9:3:575-578, 1998.

B. Ruf and M. Schmitt. Self-organizing maps of spiking neurons using temporal coding. In J. Bower, editor, *Computational Neuroscience: Trends in Research 1998* Plenum Press, 1998.

1997

O. Aichholzer. *Combinatorial & Computational Properties of the Hypercube – New Results on Covering, Slicing, Clustering and Searching on the Hypercube*. PhD thesis, IGI-TU Graz, Austria, 1997.

O. Aichholzer. The path of a triangulation. In *Proc. 13th European Workshop on Computational Geometry CG ,97*, pages 1-3, Würzburg, Germany, 1997.

O. Aichholzer, H. Alt, and G. Rote. Matching shapes with a reference point. Int'l *Journal of Computational Geometry & Applications*, 7(4):349-363, 1997.

O. Aichholzer, F. Aurenhammer, D.Z. Chen, D.T. Lee, A. Mukhopadhyay, and E. Papadopoulou. Voronoi diagrams for direction-sensitive distances (communication). In *Proc. 13th Ann. ACM Symp. Computational Geometry*, pages 418-420, Nice, France, 1997.

P. Auer. Learning nested differences in the presence of malicious noise. *Theoretical Computer Science*, 185:159-175, 1997. A preliminary version has appeared in *Proceedings of the 6th International Workshop on Algorithmic Learning Theory,* ALT,95.

P. Auer. On learning from multi-instance examples: Empirical evaluation of a theoretical approach. In D. H. Fisher, editor, *Proc. 14th Int. Conf. Machine Learning*, pages 21-29. Morgan Kaufmann, 1997.

P. Auer, P. M. Long, and A. Srinivasan. Approximating hyper-rectangles: Learning and pseudo-random sets. In Proc. 29th *Ann. Symp. Theory of Computing*, pages 314-323. ACM, May 1997.

R. Hainz, O. Aichholzer, and F. Aurenhammer. New results on minimum-weight triangulations and the LMT skeleton. *In Proc. 13th European Workshop on Computational Geometry CG ,97*, pages 4-6, Würzburg, Germany, 1997.

J. Kivinen, M. K. Warmuth, and P. Auer. The perceptron algorithm vs. Winnow: linear vs. logarithmic mistake bounds when few input variables are relevant. *Artificial Intelligence*, pages 325-343, 1997.

E. Kranakis, D. Krizanc, B. Ruf, J. Urrutia, and G. Woeginger. The VC-dimension of set-systems defined by graphs. *Journal of Discrete Applied Mathematics*, 77:237-257, 1997.

W. Maass. Bounds for the computational power and learning complexity of analog neural nets. *SIAM J. on Computing*, 26(3):708-732, 1997.

W. Maass. Fast sigmoidal networks via spiking neurons. *Neural Computation*, 9:279-304, 1997.

W. Maass. Networks of spiking neurons: the third generation of neural network models. *Neural Networks*, 10:1659-1671, 1997.

W. Maass. A model for fast analog computations with noisy spiking neurons. In James Bower, editor, *Computational Neuroscience: Trends in research*, pages 123-127, 1997.

W. Maass. Analog computations with temporal coding in networks of spiking neurons. In F. L. Silva, editor, *Spatiotemporal Models in Biological and Artificial Systems*, pages 97-104. IOS-Press, 1997.

W. Maass. Noisy spiking neurons with temporal coding have more computational power than sigmoidal neurons. In M. Mozer, M. I. Jordan, and T. Petsche, editors, *Advances in Neural Information Processing Systems*, volume 9, pages 211-217. MIT Press (Cambridge), 1997.

W. Maass. On the relevance of time in neural computation and learning. In M. Li and A. Maruoka, editors, *Proc. of the 8th International Conference on Algorithmic Learning Theory in Sendai (Japan*), volume 1316 of Lecture Notes in Computer Science, pages 364-384. Springer (Berlin), 1997.

W. Maass and T. Natschläger. Networks of spiking neurons can emulate arbitrary Hopfield nets in temporal coding. *Network: Computation in Neural Systems*, 8(4):355-372, 1997.

W. Maass and P. Orponen. On the effect of analog noise in discrete-time analog computations. In M. Mozer, M. I. Jordan, and T. Petsche, editors*, Advances in Neural Information Processing Systems*, volume 9, pages 218-224. MIT Press (Cambridge), 1997.

W. Maass and M. Schmitt. On the complexity of learning for a spiking neuron. In *Proc. of the 10th Conference on Computational Learning Theory 1997*, pages 54-61.

ACM-Press (New York), 1997. See also *Electronic Proc. of the Fifth International Symposium on Artificial Intelligence and Mathematics* (http://rutcor.rutgers.edu/~amai).

W. Maass and P. Weibel. Ist die Vertreibung der Vernunft reversibel? Überlegungen zu einem Wissenschafts- und Medienzentrum. In P.

Weibel, editor, *Jenseits von Kunst*, pages 745-747. Passagen Verlag, 1997.

B. Ruf. Computing functions with spiking neurons in temporal coding. In J. Mira, R. Moreno-Diaz, and J. Cabestany, editors, *Biological and artificial computation: From neuroscience to technology*, volume 1240 of Lecture Notes in Computer Science, pages 265-272. Springer, Berlin, 1997.

B. Ruf and M. Schmitt. Learning temporally encoded patterns in networks of spiking neurons. *Neural Processing Letters*, 5(1):9-18, 1997.

B. Ruf and M. Schmitt. Hebbian learning in networks of spiking neurons using temporal coding. In J. Mira, R. Moreno-Diaz, and J. Cabestany, editors, *Biological and artificial computation: From neuroscience to technology*, volume 1240 of Lecture Notes in Computer Science, pages 380-389. Springer, Berlin, 1997.

B. Ruf and M. Schmitt. Unsupervised learning in networks of spiking neurons using temporal coding. In W. Gerstner, A. Germond, M. Hasler, and J. Nicoud, editors, *Proc. of the 7th International Conference on Artificial Neural Networks*, volume 1327 of Lecture Notes in Computer Science, pages 361-366. Springer, Berlin, 1997.

1996

O. Aichholzer. Clustering the hypercube. *SFB-Report* F003-93, SFB ‚Optimierung und Kontrolle', TU Graz, Austria, 1996. .

O. Aichholzer and F. Aurenhammer. Classifying hyperplanes in hypercubes. *SIAM Journal on Discrete Mathematics*, 9(2):225-232, 1996.

O. Aichholzer and F. Aurenhammer. Straight skeletons for general polygonal figures. In *Proc. 2nd Ann. Int'l. Computing and Combinatorics Conf. COCOON'96*, Lecture Notes in Computer Science, volume 1090, pages 117-126, Hong Kong, 1996. Springer Verlag.

O. Aichholzer, F. Aurenhammer, S.-W. Cheng, N. Katoh, G. Rote, M. Taschwer, and Y.-F. Xu. Triangulations intersect nicely. *Discrete & Computational Geometry*, 16:339-359, 1996. Special Issue.

O. Aichholzer, F. Aurenhammer, G. Rote, and Y.-F. Xu. Constant-level greedy triangulations approximate the MWT well. In Cheng Du, Zhang, editor, *Proc. 2nd Int'l Symp. Operations Research & Applications ISORA'96*, Lecture Notes in Operations Research, volume 2, pages 309-318, Guilin, P. R. China, 1996. World Publishing Corporation.

O. Aichholzer, F. Aurenhammer, G. Rote, and Y.-F. Xu. New greedy triangulation algorithms. In *Proc. 12th European Workshop on Computational Geometry CG ,96*, pages 11-14, Münster, Germany, 1996.

P. Auer, P. Caianiello, and N. Cesa-Bianchi. Tight bounds on the cumulative profit of distributed voters. In *Proceedings of the 15th Annual ACM Symposium on Principles of Distributed Computing*, page 312, 1996. Abstract.

P. Auer, M. Herbster, and M. K. Warmuth. Exponentially many local minima for single neurons. In D. S. Touretzky, M. C. Mozer, and M. E. Hasselmo, editors, *Advances in Neural Information Processing Systems 8*, pages 316-322. MIT Press, 1996.

P. Auer and K. Hornik. The number of points of an empirical or Poisson process covered by unions of sets. *Journal of Multivariate Analysis*, 57:37-51, 1996.

P. Auer and K. Hornik. Limit laws for the maximal and minimal increments of the Poisson process. *Studia Scientiarum Mathematicarum Hungarica*, 31:1-13, 1996.

P. Auer, S. Kwek, W. Maass, and M. K. Warmuth. Learning of depth two neural nets with constant fan-in at the hidden nodes. In *Proc. of the 9th Conference on Computational Learning Theory 1996*, pages 333-343. ACM-Press (New York), 1996.

D. P. Dobkin, D. Gunopulos, and W. Maass. Computing the maximum biochromatic discrepancy, with applications in computer graphics and machine learning. *Journal of Computer and System Sciences*, 52(3):453-470, June 1996.

W. Maass. Analog computations on networks of spiking neurons (extended abstract). In *Proc. of the 7th Italian Workshop on Neural Nets 1995*, pages 99-104. World Scientific (Singapore), 1996.

W. Maass. Lower bounds for the computational power of networks of spiking neurons. *Neural Computation*, 8(1):1-40, 1996.

W. Maass. On the computational power of noisy spiking neurons. In D. Touretzky, M. C. Mozer, and M. E. Hasselmo, editors, *Advances in Neural Information Processing Systems*, volume 8, pages 211-217. MIT Press (Cambridge), 1996.

W. Maass. Networks of spiking neurons: the third generation of neural network models. *In Proc. of the 7th Australian Conference on Neural Networks 1996* in Canberra, Australia, pages 1-10, 1996.

T. Natschläger. *Raum- zeitliche Strukturen von Berechnungen in biologisch realistischen neuronalen Netzwerken*. Master's thesis, Technische Universität Graz, February 1996.

T. Natschläger. Netzwerke von Spiking Neuronen: Die dritte Generation von Modellen für neuronale Netzwerke. In *Jenseits von Kunst*. Passagen Verlag, 1996.

T. Natschläger and M. Schmitt. Exact VC-Dimension of boolean monomials. *Information Processing Letters*, 59:19-20, 1996.

B. Ruf. Pattern recognition with networks of spiking neurons. *In Workshop on Neural Networks Dynamics and Pattern Recognition*, Toulouse, pages 25-26. Onera, Centre d'Etudes et de Recherches de Toulouse, 1996.

1995

O. Aichholzer. Local properties of triangulations. In *Proc. 11th European Workshop on Computational Geometry CG ,95*, pages 27-30, Hagenberg/Linz, Austria, 1995.

O. Aichholzer, D. Alberts, F. Aurenhammer, and B. Gärtner. A novel type of skeleton for polygons. *Journal of Universal Computer Science*, 1(12):752-761, 1995.

O. Aichholzer, D. Alberts, F. Aurenhammer, and B. Gärtner. Straight skeletons of simple polygons. In *Proc. 4th Int. Symp. of LIESMARS*, pages 114-124, Wuhan, P. R. China, 1995.

O. Aichholzer, F. Aurenhammer, and G. Rote. Optimal graph orientation with storage applications. *SFB-Report* F003-51, SFB ‚Optimierung und Kontrolle', TU Graz, Austria, 1995.

O. Aichholzer, F. Aurenhammer, G. Rote, and M. Taschwer. Triangulations intersect nicely. In *Proc. 11th Ann. ACM Symp. Computational Geometry*, pages 220-229, Vancouver, Canada, 1995.

O. Aichholzer, R.L.S. Drysdale, and G. Rote. A simple linear time greedy triangulation algorithm for uniformly distributed points. *IIG-Report-Series 408*, TU Graz, Austria, 1995. Presented at the *Workshop on Computational Geometry*, Army MSI Cornell, Stony Brook, 1994.

P. Auer. Learning nested differences in the presence of malicious noise. In Klaus P. Jantke, Takeshi Shinohara, and Thomas Zeugmann, editors, *6th International Workshop, ALT,95, Proceedings*, pages 123-137. Springer, 1995. LNAI 997.

P. Auer, N. Cesa-Bianchi, Y. Freund, and R. E. Schapire. Gambling in a rigged casino: The adversarial multi-armed bandit problem. In *Proceedings of the 36th Annual Symposium on Foundations of Computer Science*, pages 322-331. IEEE Computer Society Press, Los Alamitos, CA, 1995.

P. Auer, R. C. Holte, and W. Maass. Theory and applications of agnostic PAC-learning with small decision trees. In *Proc. of the 12th International Machine Learning Conference*, Tahoe City (USA), pages 21-29. Morgan Kaufmann (San Francisco), 1995.

P. Auer, P. M. Long, W. Maass, and G. J. Wöginger. On the complexity of function learning. *Machine Learning*, 18:187-230, 1995. Invited paper in a special issue of Machine Learning.

P. Auer and M. K. Warmuth. Tracking the best disjunction. In *Proceedings of the 36th Annual Symposium on Foundations of Computer Science*, pages 312-321. IEEE Computer Society Press, 1995.

F. Aurenhammer. Guest editor's foreword of the special issue on computational geometry. *Int'l Journal of Computational Geometry & Applications*, 5:1, 1995.

F. Aurenhammer and J. Hagauer. Recognizing binary Hamming graphs in $O(n^2 \log n)$ time. *Mathematical Systems Theory*, 28:387-395, 1995.

W. J. Bultman and W. Maass. Fast identification of geometric objects with membership queries. *Information and Computation*, 118:48-64, 1995.

E. Kranakis, D. Krizanc, B. Ruf, J. Urrutia, and G. Woeginger. VC-dimensions for graphs. In M. Nagl, editor, *Graph-theoretic concepts in computer science*, volume 1017 of Lecture Notes in Computer Science, pages 1-13. Springer (Berlin), 1995.

W. Maass. Agnostic PAC-learning of functions on analog neural nets. In *Advances in Neural Information Processing Systems*, volume 7, pages 311-318, 1995.

W. Maass. Agnostic PAC-learning of functions on analog neural nets. *Neural Computation*, 7:1054-1078, 1995.

W. Maass. Vapnik-Chervonenkis dimension of neural nets. In M. A. Arbib, editor, *The Handbook of Brain Theory and Neural Networks*, pages 1000-1003. MIT Press (Cambridge), 1995.

W. Maass. On the computational complexity of networks of spiking neurons. In G. Tesauro, D. S. Touretzky, and T. K. Leen, editors, *Advances in Neural Information Processing Systems*, volume 7, pages 183-190. MIT Press (Cambridge), 1995.

W. Maass. Neuronale Netze und Maschinelles Lernen am Institut für Grundlagen der Informationsverarbeitung an der Technischen Universität Graz. *Telematik*, 1:53-60, 1995.

W. Maass and B. Ruf. On the relevance of the shape of postsynaptic potentials for the computational power of networks of spiking neurons. In *Proc. of the International Conference on Artificial Neural Networks ICANN*, pages 515-520, Paris, 1995. EC2&Cie.

W. Maass and G. Turan. On learnability and predicate logic (extended abstract). In *Proc. of the 4th Bar-Ilan Symposium on Foundations of Artificial Intelligence (BISFAI'95)*, pages 75-85, Jerusalem, 1995.

W. Maass and M. Warmuth. Efficient learning with virtual threshold gates. In Morgan Kaufmann (San Francisco), editor, *Proc. of the 12th International Machine Learning Conference*, Tahoe City, USA, pages 378-386, 1995.

1994

O. Aichholzer, H. Alt, and G. Rote. Matching shapes with a reference point. In *Proc. 10th Ann. ACM Symp. Computational Geometry*, pages 85-92, Stony Brook, New York, USA, 1994.

O. Aichholzer, H. Alt, and G. Rote. Matching shapes with a reference point. *In Proc. 10th European Workshop on Computational Geometry CG ,94*, pages 81-84, Santander, Spain, 1994.

O. Aichholzer and F. Aurenhammer. Classifying hyperplanes in hypercubes. In *Proc. 10th European Workshop on Computational Geometry CG ,94*, pages 53-57, Santander, Spain, 1994.

P. Auer and N. Cesa-Bianchi. On-line learning with malicious noise and the closure algorithm. In Setsuo Arikawa and Klaus P. Jantke, editors, *Algorithmic Learning Theory, AII'94, ALT'94,* pages 229-247. Lecture Notes in Artificial Intelligence 872, Springer, 1994.

P. Auer and K. Hornik. On the number of points of a homogeneous Poisson process. *Journal of Multivariate Analysis*, 48(1):115-156, 1994.

P. Auer and P. M. Long. Simulating access to hidden information while learning. In *Proceedings of the 26th Annual ACM Symposium on the Theory of Computing,* pages 263-272. ACM Press, 1994.

F. Aurenhammer, M. Formann, R. Idury, A. Schäffer, and F. Wagner. Faster isometric embedding in products of complete graphs. *Discrete Applied Mathematics*, 52:17-28, 1994.

Z. Chen and W. Maass. On-line learning of rectangles and unions of rectangles. *Machine Learning*, 17:201-223, 1994. Invited paper for a special issue of Machine Learning.

K. Hornik, M. Stinchcombe, H. White, and P. Auer. Degree of approximation results for feedforward networks approximating unknown mappings and their derivatives. *Neural Computation*, 6:1262-1275, 1994.

W. Maass. Neural nets with superlinear VC-dimension. In *Proceedings of the International Conference on Artificial Neural Networks 1994 (ICANN'94)*, pages 581-584. Springer (Berlin), 1994.

W. Maass. Perspectives of current research about the complexity of learning on neural nets. In V. P. Roychowdhury, K. Y. Siu, and A. Orlitsky, editors, *Theoretical Advances in Neural Computation and Learning*, pages 295-336. Kluwer Academic Publishers (Boston), 1994.

W. Maass. Computing on analog neural nets with arbitrary real weights. In V. P. Roychowdhury, K. Y. Siu, and A. Orlitsky, editors, *Theoretical Andvances in Neural Computation and Learn-*

ing, pages 153-172. Kluwer Academics Publisher (Boston), 1994.

W. Maass. Efficient agnostic PAC-learning with simple hypotheses. In *Proc. of the 7th Annual ACM Conference on Computational Learning Theory*, pages 67-75, 1994.

W. Maass. On the complexity of learning on neural nets. In J. Shawe-Taylor and M. Anthony, editors, *Computational Learning Theory: EuroColt'93*, pages 1-17. Oxford University Press (Oxford), 1994.

W. Maass. Neural nets with superlinear VC-dimension. *Neural Computation*, 6:877-884, 1994.

W. Maass, G. Schnitger, and E. Sontag. On the computational power of sigmoid versus boolean threshold circuits. In V. P. Roychowdhury, K. Y. Siu, and A. Orlitsky, editors, *Theoretical Advances in Neural Computation and Learning*, pages 127-151. Kluwer Academic Publishers (Boston), 1994.

W. Maass and G. Turan. How fast can a threshold gate learn. In S. J. Hanson, G. A. Drastal, and R. L. Rivest, editors, *Computational Learning Theory and Natural Learning System: Constraints and Prospects*, pages 381-414. MIT Press (Cambridge), 1994.

W. Maass and G. Turan. Algorithms and lower bounds for on-line learning of geometrical concepts. *Machine Learning*, 14:251-269, 1994.

B. Ruf. A stop criterion for the Boltzmann machine learning algorithm. In M. Verleysen, editor, *Proc. of the 2nd European symposium on artificial neural networks*, pages 109-116, Brussels, 1994.

1993

O. Aichholzer and H. Hassler. A fast method for modulus reduction in residue number system. In *Proc. epp'93*, pages 41-54, Vienna, Austria, 1993.

P. Auer. On-line learning of rectangles in noisy environments. In *Proceedings of the Sixth Annual ACM Conference on Computational Learning Theory*, pages 253-261. ACM Press, New York, NY, 1993.

P. Auer, P. M. Long, W. Maass, and G. J. Wöginger. On the complexity of function learning. In *Proceedings of the 5th Annual ACM Conference on Computational Learning Theory*, pages 392-401, 1993.

F. Aurenhammer. Geometric clustering and Voronoi-type partitions. *In 16th IFIP Conf. System Modelling and Optimization*, Compiegne, France, 1993.

F. Aurenhammer. Voronoi diagrams – a survey of a fundamental geometric data structure. *bit acm computing surveys ,91* (Japanese translation), Kyoritsu Shuppan Co., Ltd., pages 131-185, 1993.

M. Dietzfelbinger and W. Maass. The complexity of matrix transposition on one-tape off-line Turing machines with output tape. *Theoretical Computer Science*, 108:271-290, 1993.

A. Hajnal, W. Maass, P. Pudlak, M. Szegedy, and G. Turan. Threshold circuits of bounded depth. *J. Comput. System Sci*., 46:129-154, 1993.

W. Maass. Bounds for the computational power and learning complexity of analog neural nets. *In Proceedings of the 25th Annual ACM Symposium on Theory Computing*, pages 335-344, 1993.

W. Maass, G. Schnitger, E. Szemeredi, and G. Turan. Two tapes versus one for off-line Turing machines. *Computational Complexity*, 3:392-401, 1993.

B. Ruf. *Sequentielle und parallele Lernverfahren für Boltzmann-Maschinen*. Master's thesis, Rheinisch-Westfälische Technische Hochschule Aachen, Germany, 1993.

1992

O. Aichholzer. *Hyperebenen in Hyperkuben - Eine Klassifizierung und Quantifizierung*. Master's thesis, IGI-TU Graz, Austria, 1992.

F. Aurenhammer and J. Hagauer. Computing equivalence classes among the edges of a graph with applications. *Discrete Mathematics*, 109:3-12, 1992. Special Issue.

F. Aurenhammer, J. Hagauer, and W. Imrich. Cartesian graph factorization at logarithmic cost per edge. *Computational Complexity*, 2:331-349, 1992.

F. Aurenhammer, F. Hoffmann, and B. Aronov. Least-squares partitioning. In *Proc. 8th European Workshop on Computational Geometry CG ,92*, pages 55-57, Utrecht, the Netherlands, 1992.

F. Aurenhammer, F. Hoffmann, and B. Aronov. Minkowski-type theorems and least-squares partitioning. In *Proc. 8th Ann. ACM Symp. Computational Geometry*, pages 350-357, Berlin, Germany, 1992.

F. Aurenhammer and O. Schwarzkopf. A simple on-line randomized incremental algorithm for computing higher order Voronoi diagrams. *Int'l Journal of Computational Geometry & Applications*, 2:363-381, 1992. Special Issue.

F. Aurenhammer and G. Stöckl. Searching for segments with largest relative overlap. In *Proc. 15th IFIP Conf. System Modelling and Optimization*, Lecture Notes in Control and Information Sciences, volume 180, pages 77-84, Zürich, Switzerland, 1992. Springer Verlag.

F. Aurenhammer and G. Stöckl. Searching for segments with largest relative overlap. *Information Processing Letters*, 41:103-108, 1992.

Z. Chen and W. Maass. On-line learning of rectangles. In *Proceedings of the 5th Annual ACM Workshop on Computational Learning Theory*, pages 16-28, 1992.

Z. Chen and W. Maass. A solution of the credit assignment problem in the case of learning rectangles. In *Proceedings of the 3rd Int. Workshop on Analogical and Inductive Inference*, volume 642 of Lecture Notes in Artificial Intelligence, pages 26-34. Springer, 1992.

W. Maass and T. A. Slaman. The complexity types of computable sets. *J. Comput. Syst. Sci.*, 44:168-192, 1992. Invited paper for a special issue of the J. Comput. Syst. Sci.

W. Maass and G. Turan. Lower bound methods and separation results for on-line learning models. *Machine Learning*, 9:107-145, 1992. Invited paper for a special issue of Machine Learning.

Edited Books and Special Issues of Journals

S. Grossberg, W. Maass and H. Markram, editors, Special Issue on Spiking Neurons in Neuroscience and Technology, *Neural Networks*, vol. 14(6-7), 2001.

R. E. Burkard, W. Maass, and P. Weibel, editors,

Zur Kunst des Formalen Denkens, Passagen Verlag, Wien, 2000.

W. Maass and C. Bishop, editors, *Pulsed Neural Networks*, MIT Press, Cambridge, 1999.

P. Auer and W. Maass, editors, Special Issue on Computational Learning Theory, *Algorithmica*, vol. 22(1/2), 1-2, 1998.

F. Aurenhammer, editor, Special Issue on Computational Geometry, *Int'l Journal of Computational Geometry & Applications*, 5:1, 1995.

W. Maass, editor, *Proceedings of the 8th Annual Conference on Computational Learning Theory,* ACM-Press, 1995.

Participations in Exhibitions and other Art Projects

Permanent collection of the *Ars Electronica Center*, Linz (since 2001): Installation „Oskar" by Gerald Steinbauer, Roland Koholka, and Wolfgang Maass.

Gleich scheuen Hirschen in Wäldern versteckt zu leben, curator Jörg Schlick, Steirischer Herbst 2001: Contribution by Stefan Häusler.

Ars Electronica Festival 2001 in Linz, talk by Wolfgang Maass.

Kunst-Wissenschaft-Kommunikation, Steiermärkische Landesausstellung 2000 in Graz, H. Konrad and R. Kriesche, curators: Installation „Lernende Maschinen" by Gerald Steinbauer, Roland Koholka, and others.

Kunst-Wissenschaft-Kommunikation, Steiermärkische Landesausstellung 2000 in Graz, H. Konrad and R. Kriesche, curators: Installation „spike trains" by Harald Burgsteiner, Thomas Natschläger, and Wolfgang Maass.

Plottegg Plots 1980-2000, Neue Galerie Graz, 2000, Neuronaler Architekturprozessor (update), Manfred Wolff-Plottegg and Wolfgang Maass.

zeichenbau, Künstlerhaus Wien, 1999: Neuronaler Architekturprozessor (Prototyp), Manfred Wolff-Plottegg and Wolfgang Maass.

Symposium *Zur Physik der Kunst*, Steirischer Herbst 1999, talk by Wolfgang Maass.

Jenseits von Kunst, Peter Weibel curator, Neue Galerie Graz, 1997: Contribution by Thomas Natschläger („Netzwerke von spiking Neuronen") and Wolfgang Maass/Peter Weibel („Ist die Vertreibung der Vernunft reversibel?") to the catalog.

Technoscope, Steirischer Herbst 1997, talk by Wolfgang Maass.

Zur Kunst des Formalen Denkens, Symposium in Graz, 1997, organized jointly by the Neue Galerie Graz and the Institut für Grundlagen der Informationsverarbeitung. ■

Jobbörse

zusammengestellt von Andrea Zunegg

SoftwareentwicklerInnen für Kundenapplikationen.

Firma:	SALOMON AUTOMATION GmbH
Adresse:	A-8114 Friesach bei Graz
Ansprechperson:	Mag. Waltraud Tabernig
Telefon:	++43 3127 200 399
Fax:	++43 3127 200 22
Email:	waltraud.tabernig@salomon.at
WWW:	http://www.salomon.at

Zur Verstärkung unseres erfahrenen Teams in Österreich suchen wir SoftwareentwicklerInnen für Kundenapplikationen.

Sie sind für die selbständige Entwicklung, Anpassung, Realisierung und Inbetriebnahme von unseren kundenspezifischen Softwarelösungen verantwortlich. Sie führen Systemtests durch, betreuen unsere Kunden bei der Implementierung und sind zuständig für die umfassende Einschulung der Kunden. Dabei arbeiten Sie eng mit Projekt- und Produktmanagern zusammen.

Ihr Profil:
Sie verfügen über eine technisch fundierte Ausbildung, besitzen solide Programmierkenntnisse in C / C++ sowie Datenbanken (Oracle) und sind mit UNIX und Windows NT vertraut. Sie überzeugen durch Ihre Kommunikationsstärke, Teamfähigkeit, Belastbarkeit und Reisebereitschaft.

Lotus Notes EntwicklerIn

Firma:	SALOMON AUTOMATION GmbH
Adresse:	A-8114 Friesach bei Graz
Ansprechperson:	Mag. Waltraud Tabernig
Telefon:	++43 3127 200 399
Fax:	++43 3127 200 22
Email:	waltraud.tabernig@salomon.at
WWW:	http://www.salomon.at

Wir suchen eine/n engagierte/n und motivierte/n MitarbeiterIn zum sofortigen Eintritt als Lotus Notes EntwicklerIn, der/die bei den Begriffen Lotus Notes und Domino nicht an die neuesten Produkte einer englischen Sportwagenschmiede oder an Dominosteine denkt.

Sie sind für die Entwicklung und Betreuung des internen Informations- und Dokumentationsmanagement-Systems zuständig. Dabei entwickeln Sie eigenständig Datenbanken und die entsprechenden Applikationen.

Ihr Profil:
Fundierte Lotus Notes Programmierkenntnisse, wie Notes Client und Domino Designer (Lotus Script) sowie sehr gute Domino Administrator-Kenntnisse im Bereich Lotus Notes/Domino R 5. Gute Kenntnisse bzw. Erfahrung mit Betriebssystemen Windows NT und Windows 2000 sowie mit relationalen Datenbanken. Weiters besitzen Sie ein hohes Maß an Eigeninitiative und Teamfähigkeit.

VORSPRUNG DURCH KOMPETENZ

Logim
Logistics Information Management

Die **Firma LOGIM Software GmbH** ist weltweit auf dem Gebiet der teil- und vollautomatisierten **Logistiksysteme** tätig und ein **Unternehmen der KNAPP Gruppe**, welches weltweit zu den Top-20 Unternehmen für Materialfluss- und Handling zählt. Nach dem Einstieg eines Venture Capital Gebers liegt unser Schwerpunkt neben der laufenden **Expansion** im **Aufbau unserer Auslandsniederlassungen** und in der Vorbereitung für einen Gang an die Börse.

SOFTWARE DEVELOPER

Sie arbeiten mit modernsten Tools vom Requirement Engineering Design (UML) bis hin zur objektorientierten Realisierung (C++, Java, Corba, SQL) unter Windows - NT und UNIX, wobei unsere Standardmodule durch Parametrierung und Customizing optimal an die individuellen Bedürfnisse unserer Kunden angepasst werden. Wir erwarten Teamfähigkeit, kundenorientiertes Arbeiten, Genauigkeit und Fremdsprachenkenntnisse.

Wenn Sie ein junges expandierendes **Unternehmen mitgestalten** wollen, auf **ausgezeichnete Karrierechancen** und einen individuellen **Schulungsplan** Wert legen sowie **leistungsorientierte Entlohnung** und **interessante Sozialleistungen** schätzen, **bewerben Sie sich** bitte online unter www.logim.at oder schriftlich bei: LOGIM Software GmbH, Neuschloß 1, A-8142 Wundschuh, Tel. 03135 / 55 552 - 0.

CNSystems
The Brain & Heart Company

Als international expandierendes Unternehmen suchen wir Verstärkung für unser Team. Je nach Aufgabenstellung bieten wir Festanstellungen, Ferialjobs oder die Betreuung von Diplomarbeiten bzw. EDV-Projekten.

ProgrammiererInnen

in verschiedenen Technologie-Bereichen, darunter

User Interface Design	Java, Java2D, JFC/Swing, AWT, SWT
Internet Programming	JINI, JNDI, UPNP
Core Programming	C++, JNI, XML, Kryptografie

Es erwarten Sie leistungsgerechtes Einkommen und anspruchsvolle Tätigkeiten in einem jungen und dynamischen Team. Persönliche und fachliche Entwicklungsmöglichkeiten sind jederzeit gegeben.

Wenn Sie Ihre Erfahrungen in einer oder mehrerer dieser Technologien einbringen möchten, richten Sie bitte Ihre aussagekräftige Bewerbung an Frau Mag. Monika Petsch, petsch@cnsystems.at, CNSystems Medizintechnik GmbH, Baumkircherstrasse 1, 8020 Graz, www.cnsystems.at

SW Engineer / Database Development

Firma:	INFONOVA GmbH
Adresse:	Seering 6, A-8141 Unterpremstätten bei Graz
Ansprechperson:	Frau Simone Tomberger
Telefon:	+43 316 8003 1444
Fax:	+43 316 8003 1481
Email:	hello@infonova.at

INFONOVA Information Technology, ein Partnerunternehmen der KPMG Consulting AG, ist ein international tätige Systemhaus mit Hauptsitz in Graz und Niederlassungen in Wien, Berlin, Düsseldorf, Hamburg, München und Frankfurt.
Wir planen, bauen und integrieren Internet Netzwerke und Internet Service Applications für Telekommunikations-Unternehmen, Internet Service Provider und Firmenkunden.

Aufgabengebiet:
SW-Engineering für den Bereich User-Management & Billing-Management für Service-Provider-Gesamtlösungen

Anforderungen:
Fundierte Kenntnisse in Datenbanken (Oracle), SQL, PLSQL, C/C++, mehr als 1 Jahr Berufserfahrung.
Nice to have: Erfahrungen mit Netzwerken (TCP/IP).

Wir bieten: Raum für Selbständigkeit und Ihre persönliche Karriere.

Network Management Engineer

Firma:	INFONOVA GmbH
Adresse:	Seering 6, A-8141 Unterpremstätten bei Graz
Ansprechperson:	Frau Simone Tomberger
Telefon:	+43 316 8003 1444
Fax:	+43 316 8003 1481
Email:	hello@infonova.at

INFONOVA Information Technology, ein Partnerunternehmen der KPMG Consulting AG, ist ein international tätige Systemhaus mit Hauptsitz in Graz und Niederlassungen in Wien, Berlin, Düsseldorf, Hamburg, München und Frankfurt.
Wir planen, bauen und integrieren Internet Netzwerke und Internet Service Applications für Telekommunikations-Unternehmen, Internet Service Provider und Firmenkunden.

Aufgabengebiet:
Im Bereich Network Managemant konzipieren, realisieren und integrieren Sie im Team Software-Lösungen für das Management komplexer heterogener IP Netzwerke. Bei entsprechendem Engagement haben Sie sehr gute Entwicklungsmöglichkeiten.

Anforderungen:
Mehrjährige Erfahrung in der SW-Entwicklung (C/C++, Perl etc.), grundlegende Netzwerk- und IP-Kenntnisse, sowie Grundkenntnisse in Unix (AIX). Teamfähigkeit sowie selbstständiges Arbeiten setzen wir voraus.

Wir bieten: Raum für Selbständigkeit und Ihre persönliche Karriere. Unsere Firmenkultur ist geprägt von jungen, motivierten Teams, die mit Begeisterung die Internet Zukunft **mitgestalten.**

Technischer Redakteur

Firma:	INFONOVA GmbH
Adresse:	Seering 6, A-8141 Unterpremstätten bei Graz
Ansprechperson:	Frau Simone Tomberger
Telefon:	+43 316 8003 1444
Fax:	+43 316 8003 1481
Email:	hello@infonova.at

INFONOVA Information Technology, ein Partnerunternehmen der KPMG Consulting AG, ist ein international tätige Systemhaus mit Hauptsitz in Graz und Niederlassungen in Wien, Berlin, Düsseldorf, Hamburg, München und Frankfurt.
Wir planen, bauen und integrieren Internet Netzwerke und Internet Service Applications für Telekommunikations-Unternehmen, Internet Service Provider und Firmenkunden.

Aufgabengebiet
Ihre Aufgabe umfasst die Konzeption, die Erstellung und die Produktion von technischen Dokumentationen.
Sie sind verantwortlich dafür, dass die technische Dokumentation für den Anwender (First Level Support bis Management) zielgruppengerecht aufbereitet ist und arbeiten dabei eng mit unserem Entwicklungsteam zusammen.

Anforderungen
Wir erwarten gutes technisches Grundverständnis, perfekte Beherrschung der Office Anwendungen, wie MS Word, MS PowerPoint, MS Visio sowie HTML Grundkenntnisse. Programmierkenntnisse und Datenbankkenntnisse runden Ihr Profil ab.
Gute analytische und konzeptionelle Fähigkeiten setzen wir voraus. Sie haben ein gutes Gefühl für Sprache und Freude am Schreiben. Ebenso haben Sie gute bis sehr gute Kenntnisse der englischen Sprache.

Wir bieten: Raum für Selbständigkeit und Ihre persönliche Karriere. Unsere Firmenkultur ist geprägt von jungen, motivierten Teams, die mit Begeisterung die Internet Zukunft mitgestalten.

C++ Entwickler mit MFC-Erfahrung

Firma:	KPMG InfoDesign GmbH
Adresse:	Seering 7, 8141- Unterpremstätten bei Graz
Ansprechperson:	Frau Margit Machinger
Telefon:	+43 316 8003 8041
Fax:	+43 316 8003 8480
Email:	margit.machinger@kpmg-infodesign.com
Homepage:	kpmg-infodesign.com

KPMG InfoDesign ist ein Full Service Anbieter für SAP- und eSolutions und betreut vor allem Großkunden in den Geschäftsfeldern E-Business, SAP-Technologies, Portallösungen, Mobile, UMS & eMarketing- bzw. Geomarketing-Solutions, Intranet und Knowledge Management sowie Technology Consulting und Digital Design.

Für den Standort Graz suchen wir einen „C++ Entwickler mit MFC-Erfahrung“

Ihr Profil:
* Programmiererfahrung in C/C++ (MFC)
* Kenntnisse in Java (J2EE), SQL, XML und mit Datenbanken (Oracle, MS SQL, MySQL) sind von Vorteil

Sie sind offen, engagiert, arbeiten eigenverantwortlich und verfügen über konzeptionelle und organisatorische Fähigkeiten sowie ein sicheres Auftreten.
Aufgrund der internationalen Ausrichtung unserer Unternehmensgruppe sind gute Englisch-Kenntnisse und eine hohe Reisebereitschaft von Vorteil. ■

Die Jobbörse

Wenn auch Ihre Firma Stellen im Bereich der Telematik zu vergeben hat, nützen Sie unsere Jobbörse. Nähere Informationen darüber erhalten Sie unter Tel. 0316/873-5011 oder per Email redaktion@tiv.tu-graz.ac.at.

Die Jobbörse gibt es auch unter http://www.tiv.tu-

Diplomarbeiten Telematik Jan. - Feb. 2002

zusammengestellt mit Unterstützung der Forschungs- & Technologieinformation

Bretterklieber, Thomas

Entwicklung eines Modulgenerators für integrierte digitale Filterstrukturen

Die digitale Signalverarbeitung hat in den letzten Jahrzehnten auf technischem und naturwissenschaftlichem Gebiet eine große Bedeutung erlangt. Zu ihren Hauptanwendungen zählen digitale Filter, die sich aufgrund ihrer regelmäßigen Strukturen sehr gut für eine Realisierung in VLSI eignen. Diese Arbeit behandelt die Implementierung eines Modulgenerators für FIR-Filter, IIR-Filter und Dezimationsfilter. Der Generator ermöglicht es, Filterlayouts einzelner Filter sowie ganzer Filterkaskaden weitgehend automatisiert zu erzeugen. Dabei greift der Generator auf eine charakterisierte Filterzellbibliothek zurück und erstellt die Beschreibung des Filterdatenpfades auf Layoutebene und funktionaler Ebene. Die entsprechende Filtersteuerung wird verhaltensmodelliert bereitgestellt und nach dem Syntheseschritt mit dem Full-Custom-Layout des Datenpfades kombiniert. Die Filterzellen sind sowohl in statischer als auch in dynamischer CMOS-Logik ausgeführt und hinsichtlich ihres Flächenbedarfs optimiert. Der Generator wurde in C++ implementiert und erlaubt die optimale Einbindung des Filterentwurfs in eine heterogene Designumgebung.
Betreuer: Söser, Peter

Kuschel, Thomas

Funknetzanbindung eines interaktiven IR-Bewegungsmelders

Ein bestehender autonomer interaktiver Infrarot-Bewegungsmelder wird um ein Funknetz in Master-Slave-Konfiguration erweitert. Zur Lösung kommt eine Mikroprozessoranwendung im neuen 868 MHz ISM-Band mit einem Transceiver-IC AT86RF211 von Atmel Grenoble (vormals Thomson-CSF). Das Netzwerk wird durch ein eigenentwickeltes Modem an einem PC mit LabView ® -Software (National Instruments) gesteuert. Es können Daten, vornehmlich digitale Sprach-Dateien, zu den Bewegungsmeldern bidirektional übertragen werden. Die Datenübertragungsrate über Funk in FSK-Modulation liegt bei 38 kbit/s. Die Verbindung zwischen PC und Modem erfolgt über die serielle Schnittstelle mit 115 kbit/s. Zur Kommunikation wird ein stark vereinfachtes HDLC-Protokoll verwendet, das mit einem CRC16 (16 bit-Cyclic Redundancy Code) zur Fehlererkennung versehen ist. Die Steuerung über den Master kann bis zu maximal 127 Netzwerkteilnehmern (IR-Bewegungsmelder) adressieren und steuern.
Betreuer: Leitgeb, Erich; Birnbacher, Ulla; Mair, Werner (MicroElectronicDesign Spath KEG)

Bajzek, Manfred

Datenkonvertierung für eine spezielle Internetpräsentation

Die Diplomarbeit entstand im Rahmen der Implementierung des digitalen Museums des IICM. Sie beschäftigt sich mit der Datenaufbereitung (Extraktion der Daten aus einer am IICM dafür implementierten relationalen Datenbank) und der automatisierten Konvertierung dieser Daten. Die Daten werden in der Datenbank in Form von Queries zusammengefasst und über eine ODBC-Schnittstelle mit Hilfe eines Perl-Moduls ausgelesen. Durch den speziellen Aufbau des Namens einer Query und durch bestimmte Befehlscodes in deren Feldnamen, werden die Datensätze entsprechend aufgeteilt und konvertiert. Die konvertierten Daten werden in ein entsprechendes Layout eingebunden und als HTML-Dokumente abgespeichert. Diese HTML-Dokumente werden in einer lokalen Verzeichnisstruktur in entsprechenden Dateistrukturen abgelegt. Diese Dateistrukturen sind so konzipiert worden, dass die lokale Verzeichnisstruktur als Basis für den Export auf verschiedene Zielplattformen gesehen werden kann. Zu diesen Zielplattformen zählen der Hyperwave Information Server, der Apache-Server und eine DVD-Version. Ausgehend von dieser lokalen Verzeichnisstruktur werden mit Hilfe von verschiedenen Tools die Daten auf die Zielplattformen kopiert bzw. konvertiert. Das digitale Institutsmuseum wurde im Juni 2001 im Internet unter much.iicm.edu für die Öffentlichkeit zugänglich gemacht.
Betreuer: Maurer, Hermann ■

Impressum

Medieninhaber/Verleger/Vertrieb: Telematik-Ingenieur-Verband (TIV), Inffeldgasse 16b, A-8010 Graz, Tel: 0316/873-5017, Fax: 0316/873-5050, Email: office@tiv.tu-graz.ac.at, Web: www.tiv.tu-graz.ac.at
Chefredakteur: DI Dr. Bernhard Rinner
Redaktion: DI Dr. Bernhard Rinner, Email: redaktion@tiv.tu-graz.ac.at
Satz, Layout, Grafik: DI Klaus D. Zesar
Anzeigenkontakt: Andrea Zunegg, Tel: 0316/873-5011
Kolumnen: Alexandra Mörth, DI Klaus D. Zesar
Druck: Druckerei Dorrong, Graz
Erscheinungsweise: 4x jährlich
Bezug: Einzelpreis € 5,--; Jahresabo € 20,--

Gedruckt mit Förderung des Bundesministeriums für Bildung, Wissenschaft und Kultur. Die Telematik erscheint in wissenschaftlicher Zusammenarbeit mit den einschlägigen Instituten der TU Graz.

Telematik-Ingenieur-Verband
Inffeldgasse 16/2, A-8010 Graz