Overview on Applications: Is (advanced) mathematics useful? CO@W Berlin

Martin Grötschel

2.10.2015

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- Forschungszentrum MATHEON
- Konrad-Zuse-Zentrum für Informationstechnik Berlin (ZIB)

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Remark

- For some of the photos and pictures shown in the lecture the copy right is unclear. That is why these pictures have been removed from the slides.

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About mathematics

- The most challenging intellectual endeavor of mankind
- Beauty, esthetics
- Eternal truths
- But mathematics is more than that: an indispensable tool for almost all other scientific and economical activities

The role of mathematics in this century

- It is my firm belief – not only an advertisement pitch – that mathematics is THE scientific endeavor of the 21st century.
- Advanced sciences and industries have learned that.
- Unfortunately this is hardly known by the general public.
- But also many mathematicians are not aware of this role.


The role of mathematics in this century

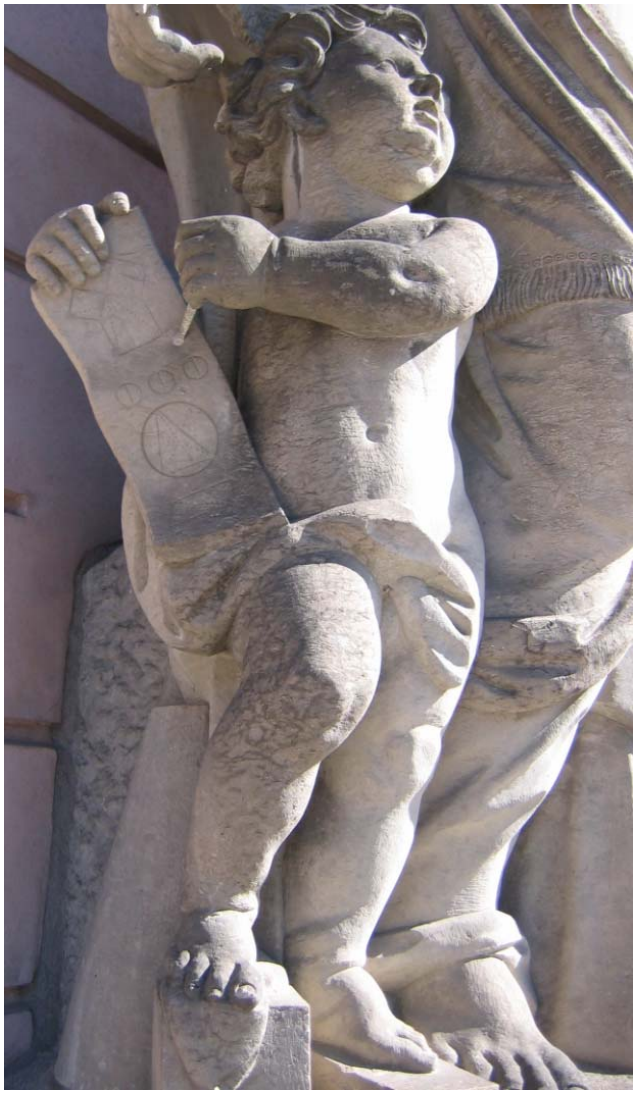
Moreover

- If a country wants to grow, it needs to improve the skills of its population, and in particular, its mathematical education. And the mathematical education has to focus on both, the elementary and the top level.
  (Eric Hanushek, KunMo Chung at MENAO)
- If a company wants to stay competitive, it needs mathematics.
- To understand the world (by scientific means), mathematics is indispensable.


My favourite photo, ICM 2002

Considering maths as useful?

- In front of the Zeughaus in Berlin



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Considering maths as useful?

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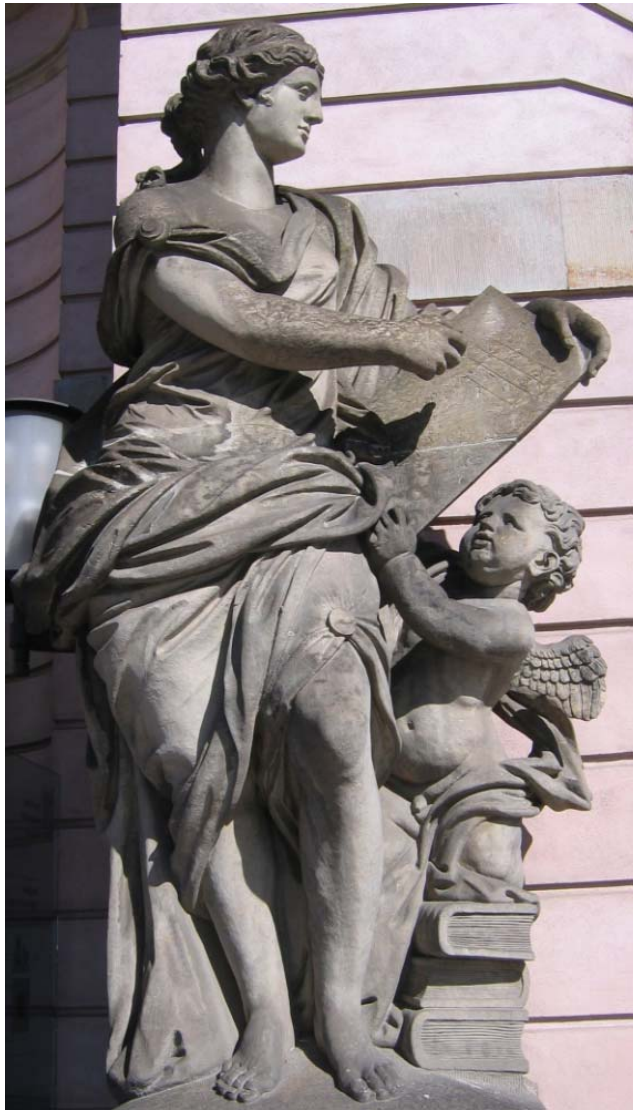

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What do I mean by „useful“?

- Karl Weierstrass (1860): Every continuous function on a compact set assumes a maximum and a minimum.
- Important theorem, but useless in practice.
- Claus Scheiderer (1989): The stability index of an affine real variety of dimension n>0 is n(n+1)/2.
- Do you understand it?
- With the Dijkstra algorithm of 1959 (and suitable data structures) a shortest path between two nodes of a weighted directed graph with n nodes and m arcs can be computed in O(n log(n) + m) time.
- A result that everyone employs every day (without knowing it).

What is efficiency?

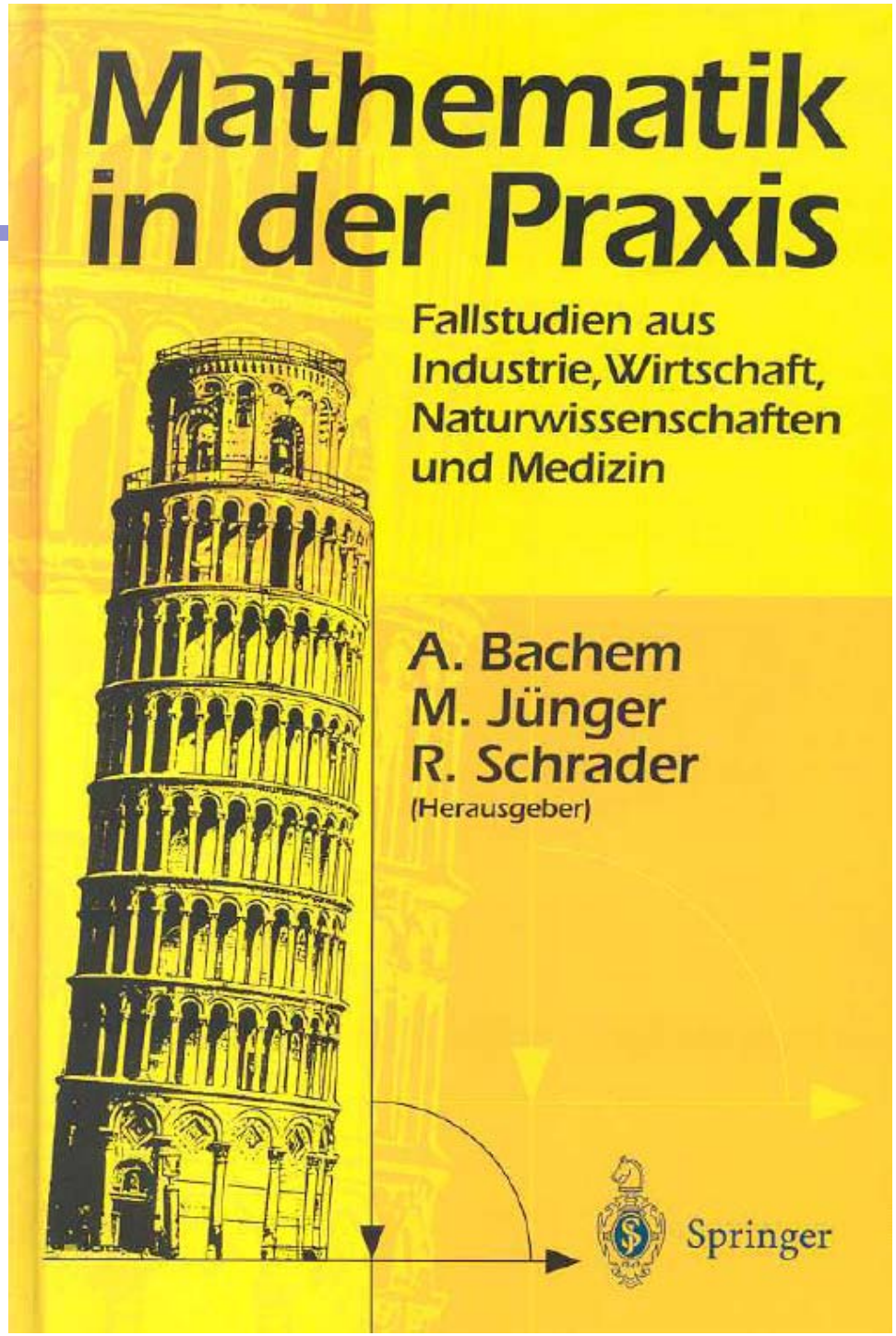
- Complexity Theory
- Polynomial time solvability (fast): Dijkstra's algorithm
- NP-completeness (difficult)
- Practical efficiency

What is optimization?

The general standard example:

- Given a set S and a function f from S to an ordered set T. Find a point x in S such that f(x) is as large or as small as possible (according to the ordering of T).
- Usually, S is a subset of the n-dimensional vector space over the reals (in theory); in practice we can only compute with rational numbers, though.
- And also usually, the ordered set T is the set of real or rational numbers.

Proceedings of a meeting of the DMV,
German Mathematical Society,
1993



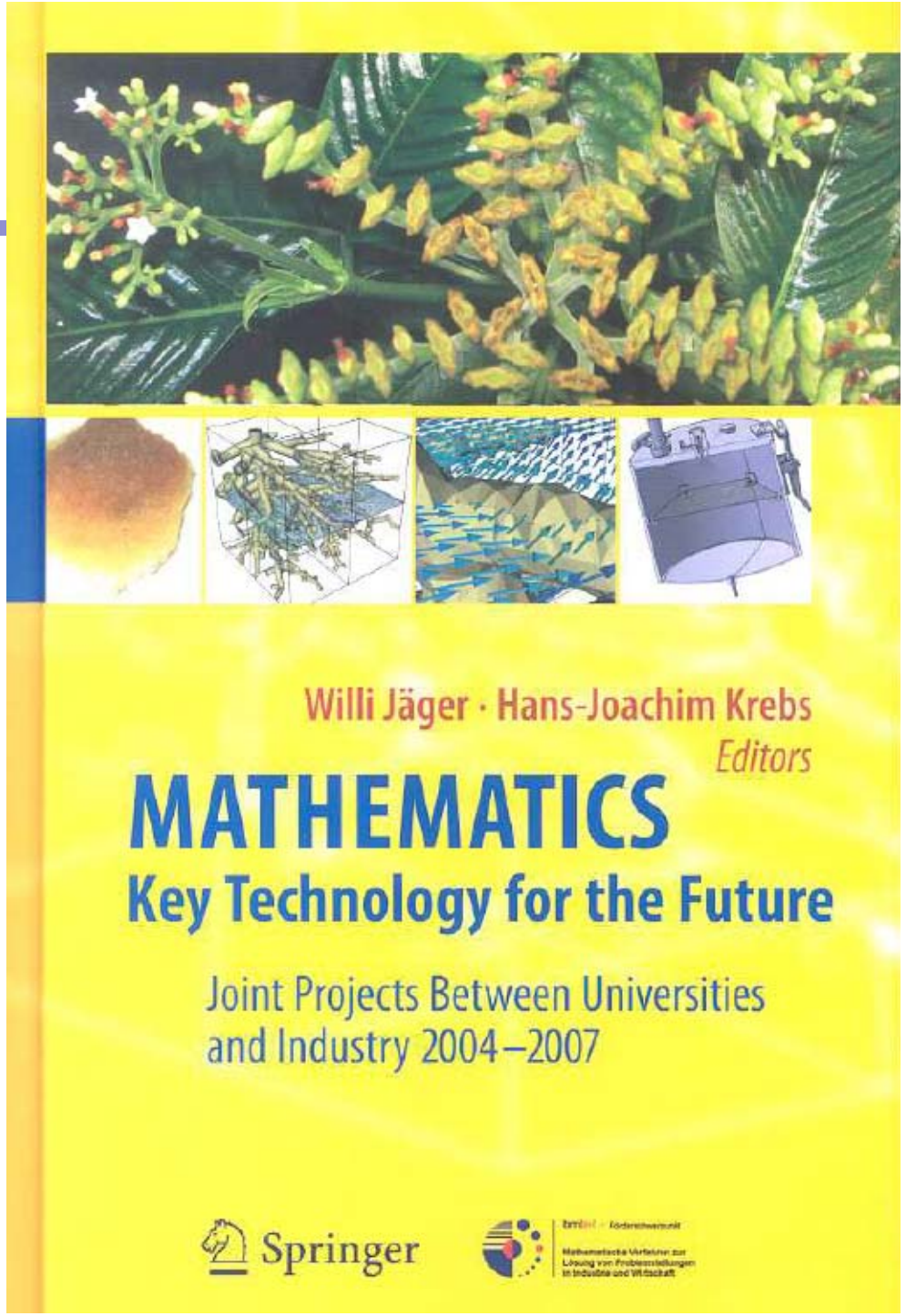
BMBF

Support Program of the Federal Ministry of Education and Research

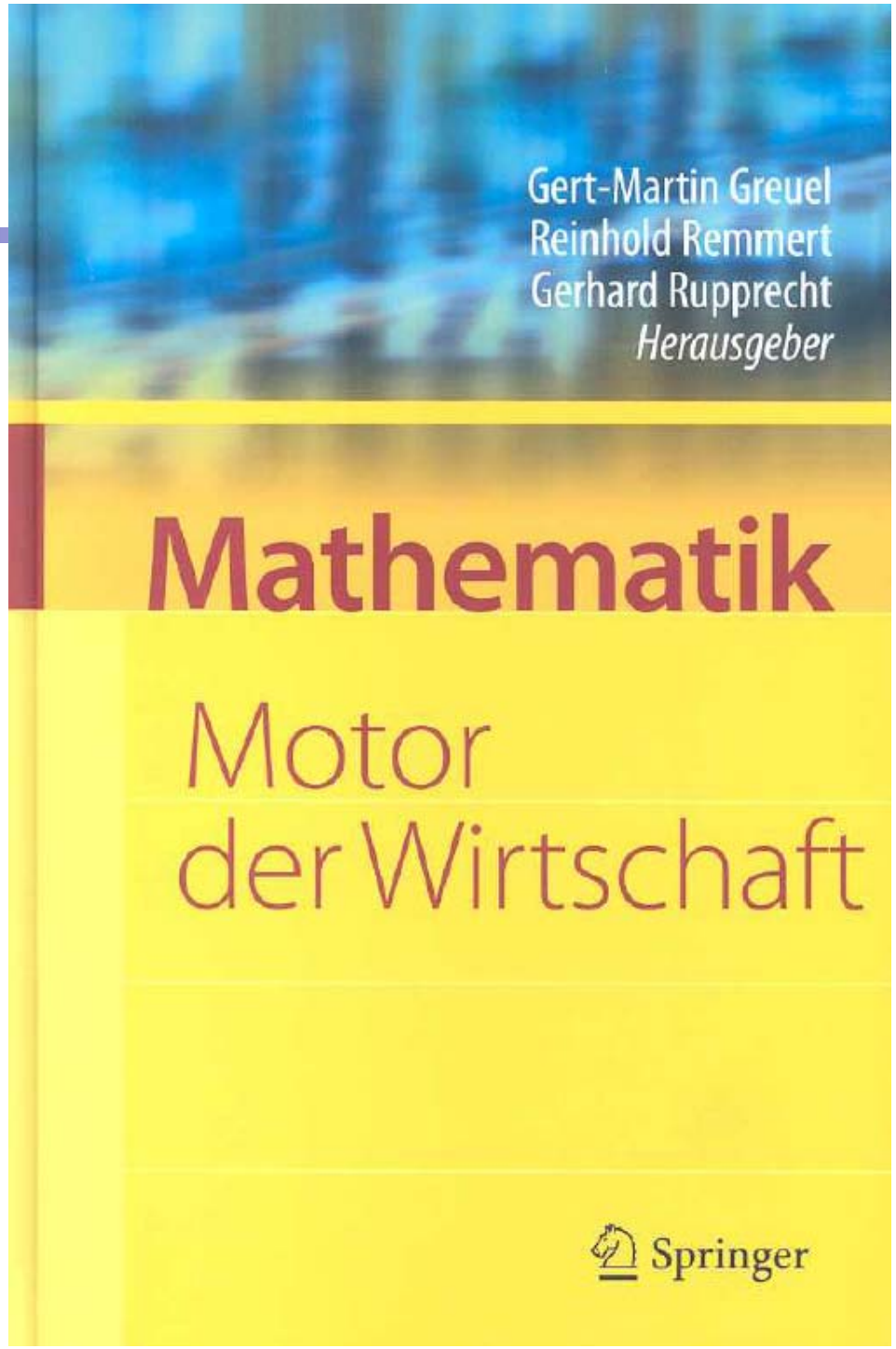
Strengthening of Applied Math Research in Germany

So far 6 periods:
1993-1997, 1997-2001
2001-2004, 2004-2007
2007-2010, 2010-2013

Current 2014-2017:
Mathematik für Innovationen in Industrie- und Dienstleistungen



An inititative of the German Industry for the Year of Mathematics 2008



Statements about mathematics by DAX CEOs

- Die Denkweise der Allianz ist mathematisch geprägt. (Rupprecht, Allianz)
- Mathematisches Können ist ein Wettbewerbsvorteil. (Zetsche, Daimler)
- Universelle Anwendbarkeit macht Mathematik zur Königsdisziplin. (Zetsche, Daimler)
- Unternehmensführung ohne Mathematik ist wie Raumfahrt ohne Physik. (Kagermann, SAP)
- Gerade bei einem chemisch-pharmazeutischen Unternehmen wie Bayer sind Numerik, Optimierung, Differentialgleichungen und Statistik in den wichtigen Bereichen Wirkstoffsuche und klinische Studien, Prozessoptimierung und Logistik nicht mehr wegzudenken. (Wenning, Bayer)

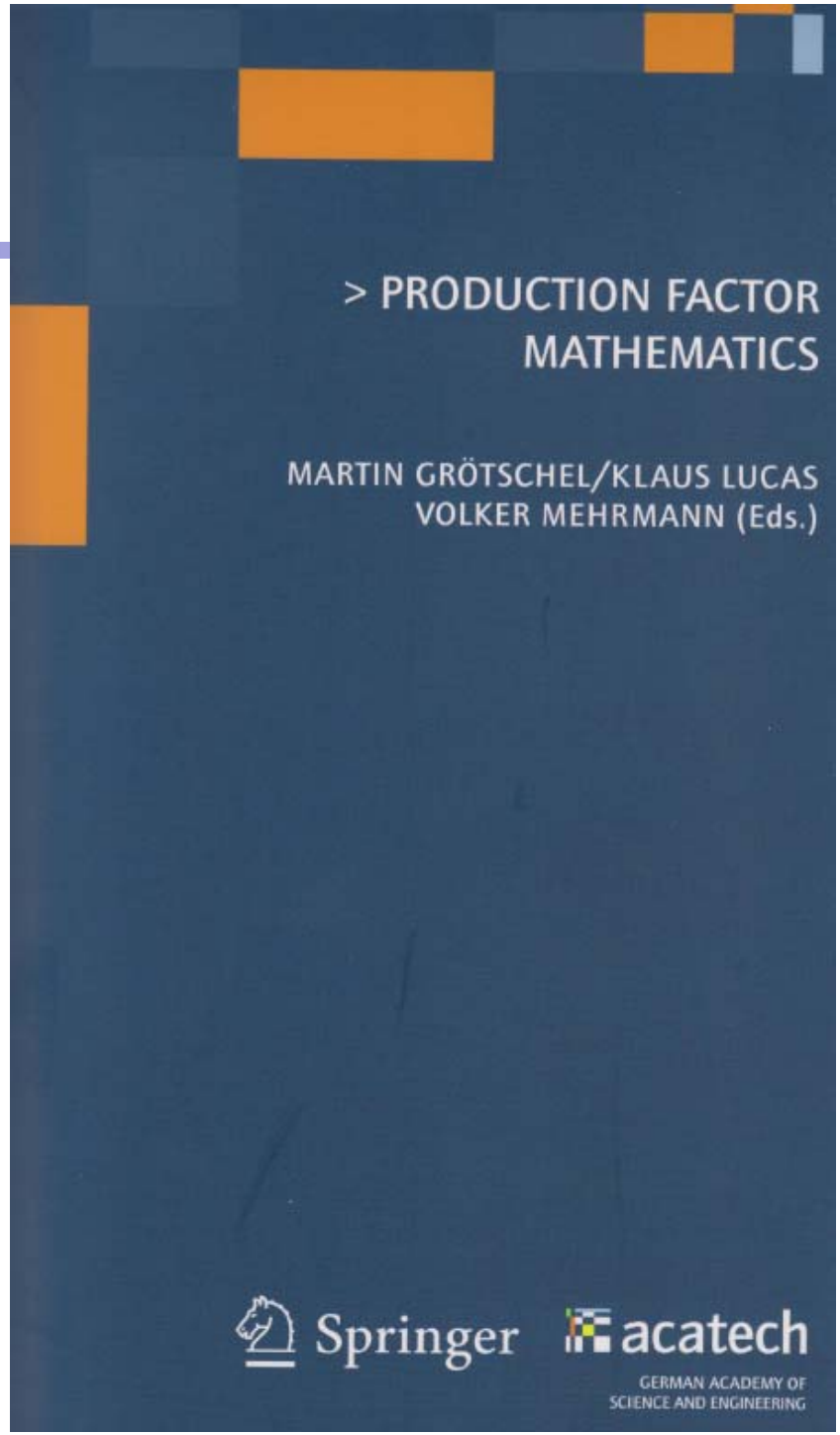
- „Ohne Mathematik tappt man doch immer im Dunkeln." (Werner von Siemens)

Some ZIB/MATHEON partners from industry

acatech German National Academy of Engeneering

(The Book appeared 2010, German version in 2008)

downloadable from my Web site



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SEARCH

AA Impressum

RESEARCH | INSTITUTE | RESEARCH SERVICES | MEMBERS | TRAINING & OUTREACH | CONTA

The Zuse Institute Berlin (ZIB)

is an interdisciplinary research institute for applied mathematics and data-intensive high-performance computing. Its research focuses on modeling, simulation and optimization with scientific cooperation partners from academia and industry.

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Our latest news

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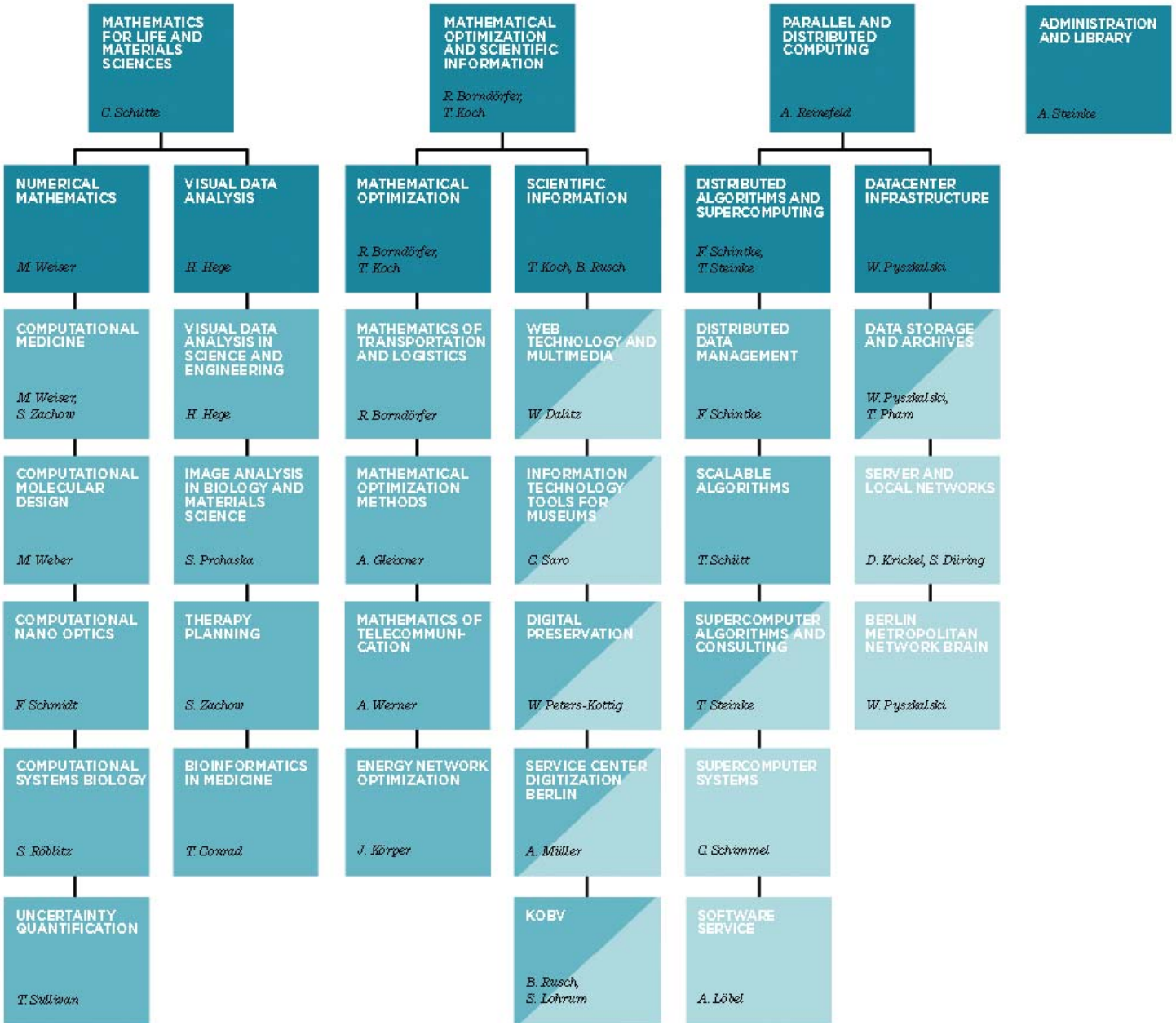
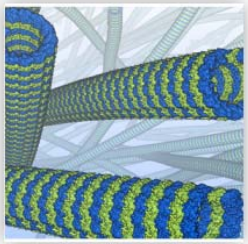
Upcoming events

Organisational structure of ZIB

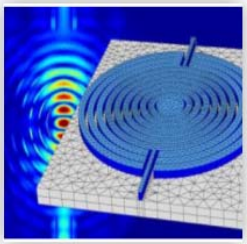


ZIB's Research Focus Areas

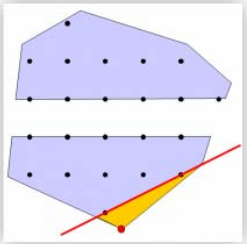
-- Research Focus Area
-- Solutions for Individualized Medicine



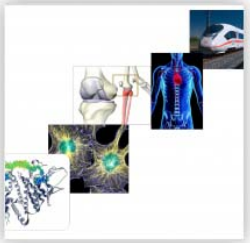
-- Research Focus Area
-- Molecular and Biological Processes



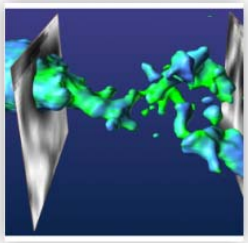
-- Research Focus Area
-- Materials and Optical Processes



-- Research Focus Area
-- Combinatorics and MINLP

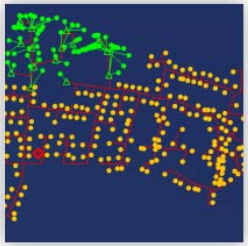


-- Research Focus Area
-- MSO for Multiscale Systems



-- Research Focus Area
-- Robust Solutions under Uncertainty

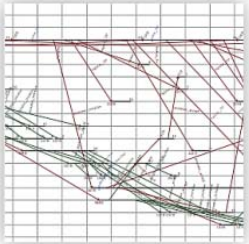
-- Research Focus Area
-- Digital Humanities



-- Research Focus Area
-- Efficient Infrastructure and Logistics

-- Research Focus Area
-- Large-Scale Data Management, Curation & Analysis

-- Research Focus Area
-- Highly Parallel Computing



-- Research Focus Area
-- Scalable and Fault-Tolerant Algorithms

http://www.zib.de/research

TU Berlin, Mathematisches Institut

Institut für Mathematik
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Institut für Mathematik

Mathematikgebäude der TU Berlin

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Gehe zu: 9003
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10623 Berlin

TU Berlin

Technische Universität Berlin
Faculty II – Mathematics and Natural Sciences
Institute of Mathematics

Deutsche Version

Wissenschaftsjahr 2008
Mathematik
Alles, was zählt

Local MathNet Guide

Visitors Guide

TU Berlin - Fakultät II
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in Keywords

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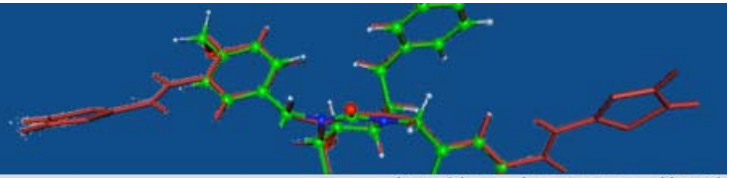
- Events, Meetings and Dates
- Mathematics Calendar Berlin-Potsdam

Sorry, but pages marked with are currently only available in German language.

MATHEON

Forschungszentrum MATHEON
Mathematik für Schlüsseltechnologien



Anmelden Impressum Kontak

Startseite | Forschung | Transfer | Schule | Presse | Über uns | Neuigkeiten

Prof. Thorsten Koch receives Google Faculty Research Award: Für Forschungsarbeiten zu „Mixed Integer Optimization as a Service" erhält Prof. Dr. Thorsten Koch (ZIB/TUB) einen Google Faculty Research Award. Prof. Koch leitet die Abteilung Wissenschaftliche Information am ZIB und ...

Das Forschungszentrum MATHEON

entwickelt Mathematik für Schlüsseltechnologien und unterstützt Partner in Industrie, Wirtschaft und Wissenschaft. Schule und Öffentlichkeit bilden einen weiteren Fokus unserer Aktivitäten. MATHEON wird von den drei Berliner Universitäten (FU, HU and TU) und den Forschungsinstituten (WIAS und ZIB) gemeinsam getragen.

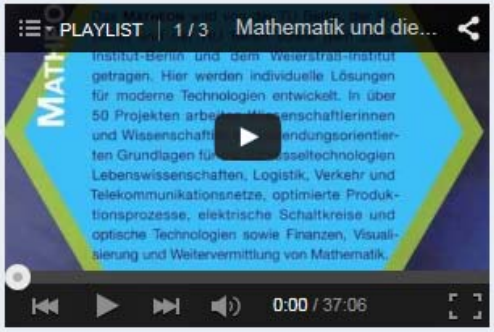
GAMM-Preis für Joscha Gedicke: Dr. Joscha Gedicke vom WIAS und MATHEON-Mitglied hat einen der vier diesjährigen Preise der Dr.-Körper-Stiftung der Gesellschaft für Angewandte Mathematik und Mechanik (GAMM) erhalten. ...

Mathematischer Modellbau leicht verständlich aufbereitet: Dr. Jannik Matuschke von der TU Berlin wird mit dem Klaus Tschira Preis für verständliche Wissenschaft ausgezeichnet. ...

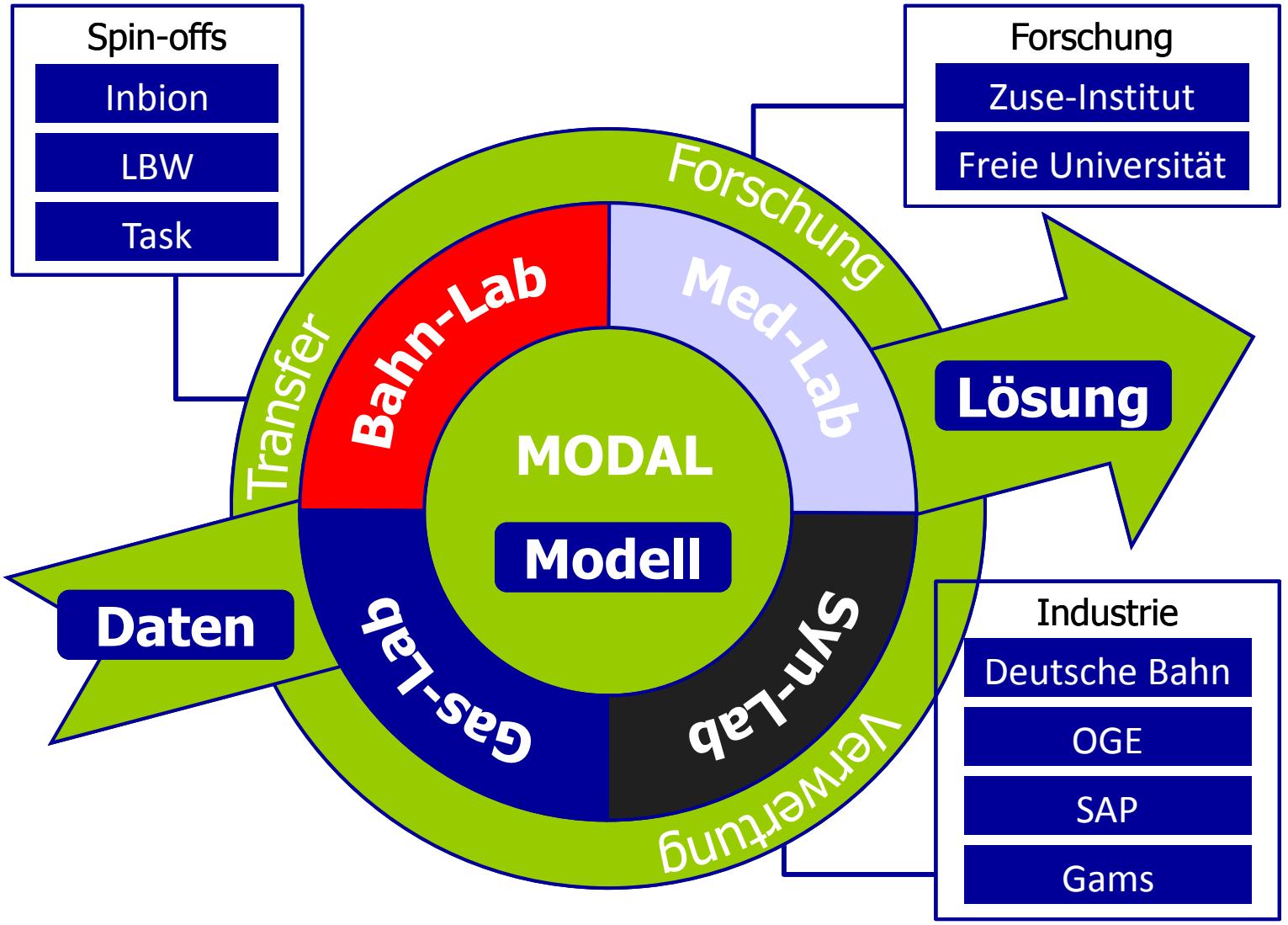
10. Vektoria Award, : dem Kreativpreis für Schüler und Schülerinnen von CASIO! ...

Aufgelesen

- Spätbabylonische Liebe zur Mathematik (Spiegel online)
- Die Mathematik des Riechens (Bild der Wissenschaft)
- Mathematikerin Hélène Esnault (Tagesspiegel)
- Zahlenplattform Imaginary.org (Spiegel online)
- Rechenschwäche. (Berliner Zeitung)
- Die neue „Miss Germany" ist gekürt (Berliner Zeitung)
- Neue Methoden im Mathe-Unterricht (Arte TV)
- Die Optimierung der Welt (Tagesspiegel)
- Mathe-Prof als YouTube-Star (Spiegel Online)



Forschungscampus MODAL: BMBF and industry supported



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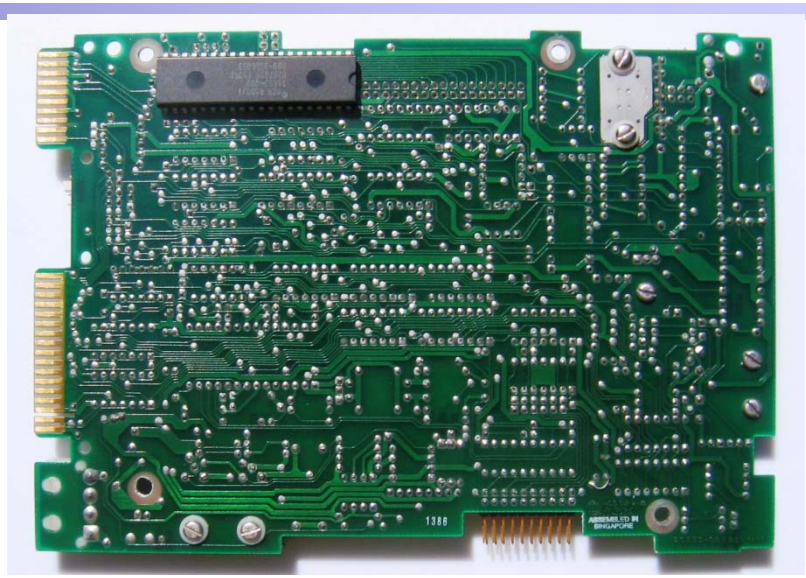
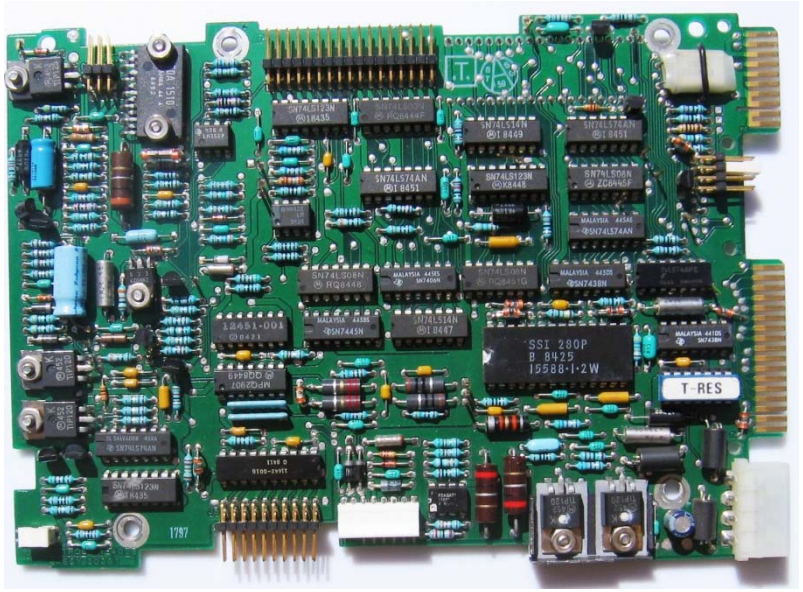
Printed Circuit Board Drilling and Assembly Machines





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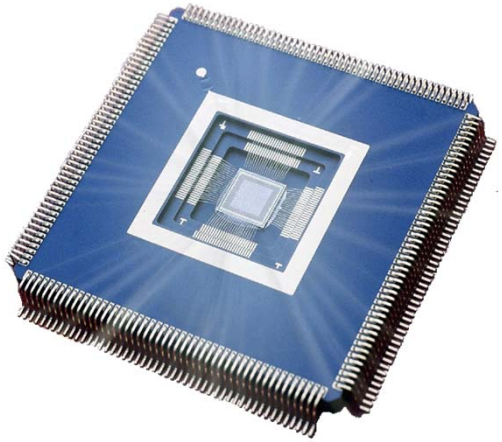
Design, Verification and Production of Chips



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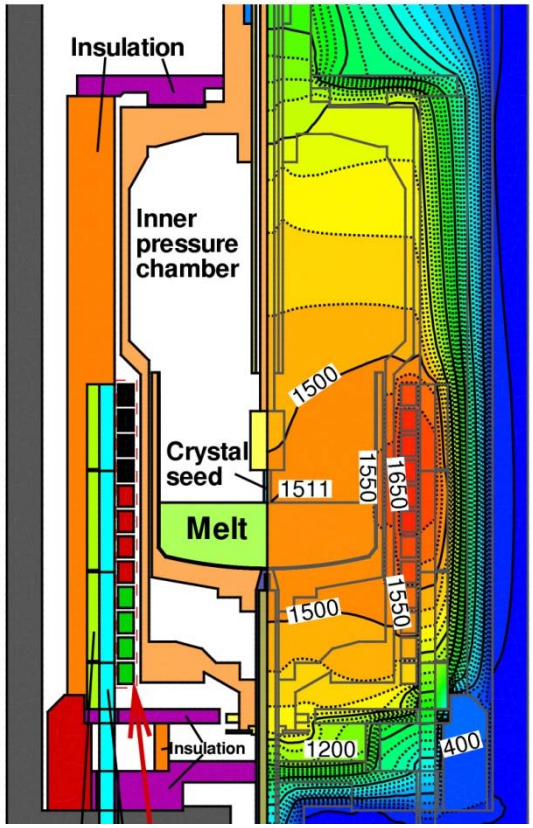
Chystal growth (MATHEON C9)

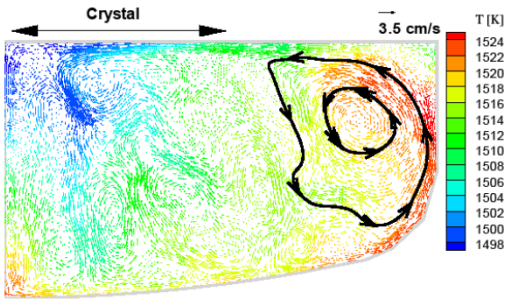


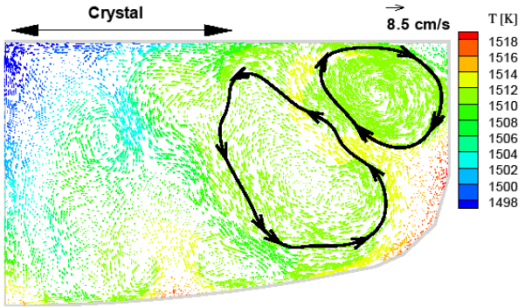
Control of the process via magnetic fields

to optimize

- temperature
- flow of the molten mass
- form of solidification surface

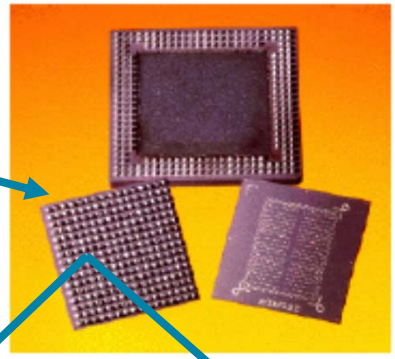
without and with magnetic field





Soldering: Trouble on Chips and Printed Circuit Board

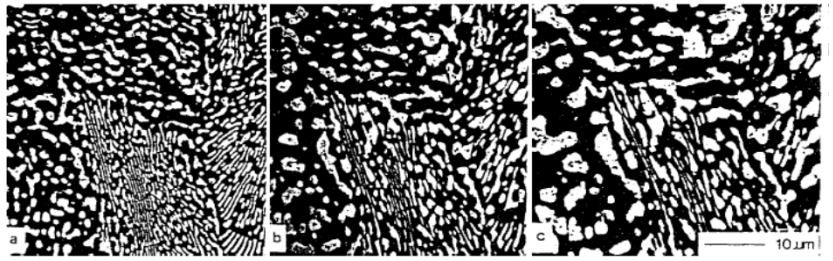
Phase separation and coarsening



Balls of solder (e.g. tin-lead-alloy) establish electrical contact to the chip.

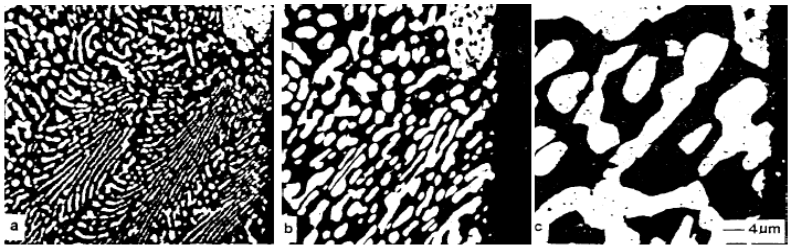
switched on

room temperature



2 hs 17 days 63 days

125 °C

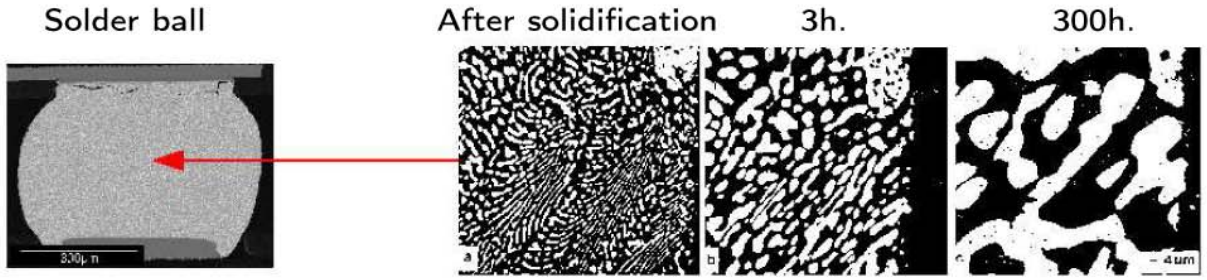


0 hs 3 hs 13 days

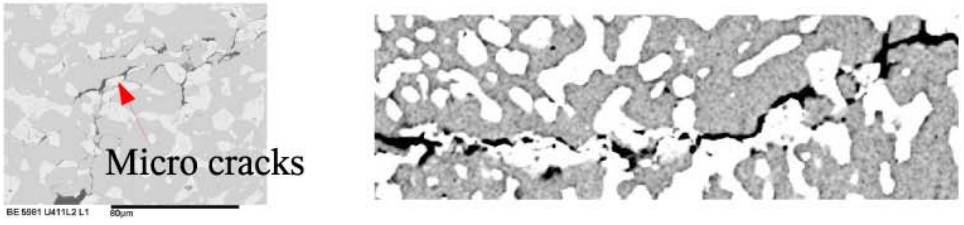
Background

Morphology in solder joints

- Phase separation and Coarsening



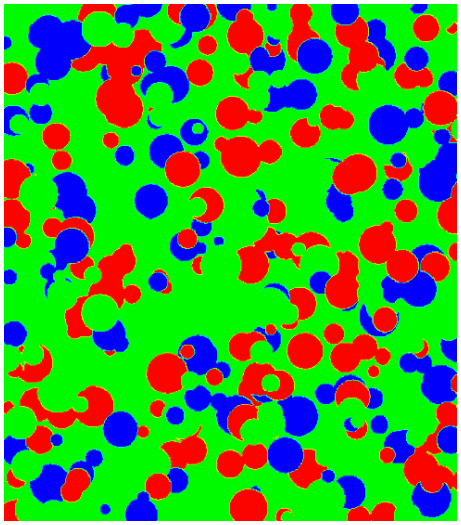
- Crack initiation and propagation



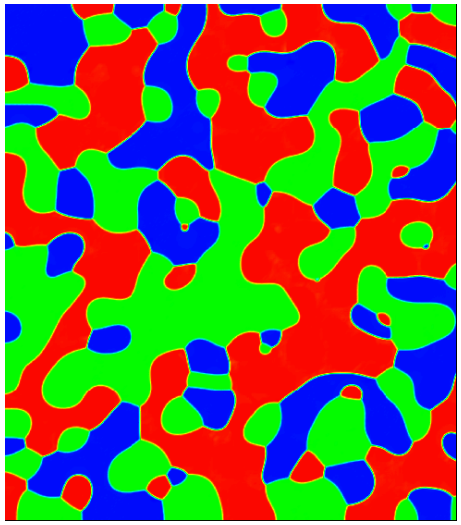
ELFNET Roadmap 2007:

High priority: Models for microstructure evolution + cracking

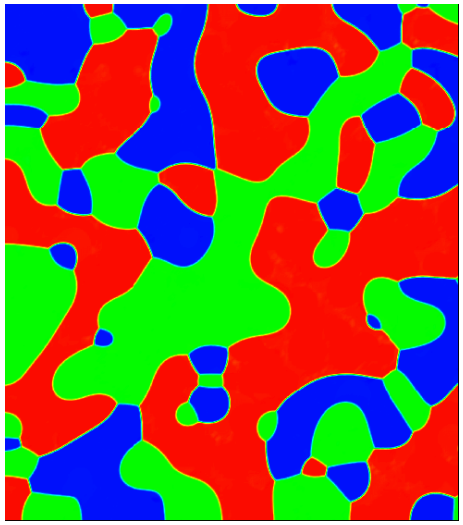
MATHEON-Projekt: Modelling and Simulation of Phase Separation



t=0



t=100

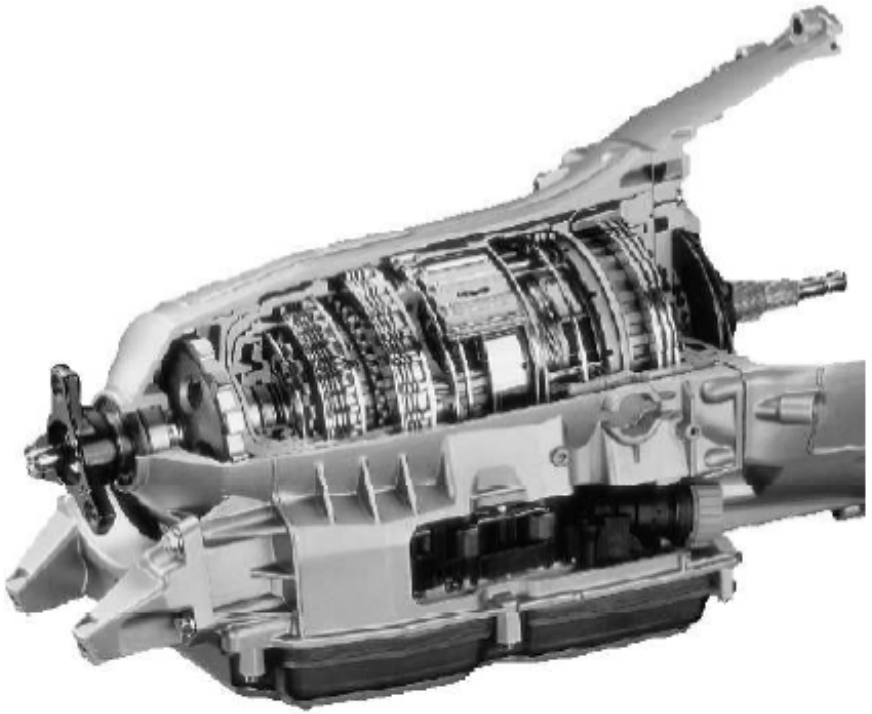


t=600

Optimization of automatic gear boxes

Modellbasierte Regelung von Automatikgetrieben

Dissertation P. Hamann, Daimler AG



Herlitz at Falkensee (Berlin)

Optimization and control of transport devices (such as elevators, stacker cranes) in factories

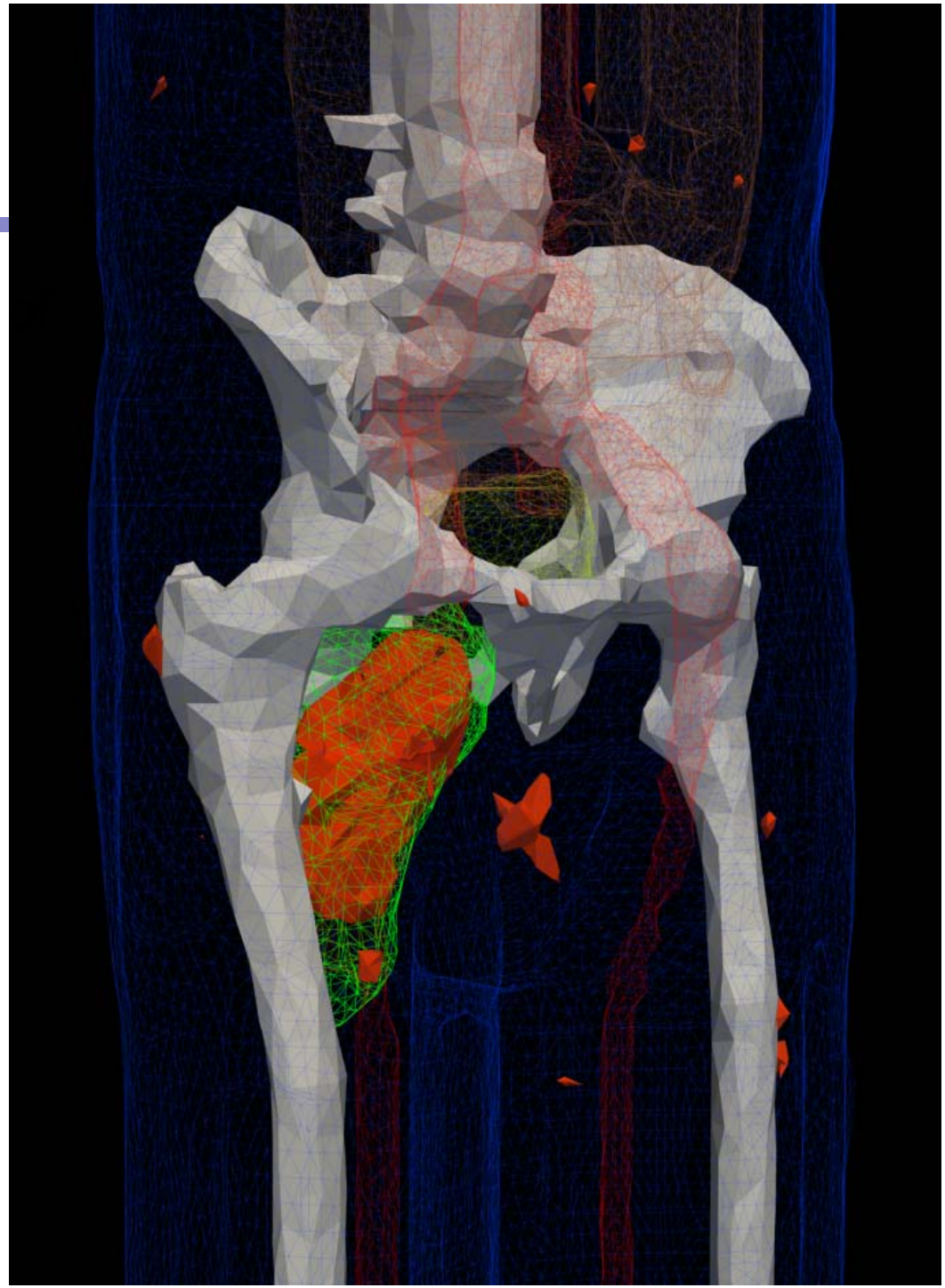
Herlitz, Falkensee

Traffic and Transport

Supereinsatz. In Berlin und Brandenburg mussten die Gelben Engel letztes Jahr mehr als 240 000 Mal ausrücken, um Havaristen in der Hauptstadt und auf 1700 Autobahnkilometern wieder flottzumachen – ein Rekordeinsatz. Einen Rückgang von zehn Prozent bei den Pannen registrierten dagegen die Gelben Engel in Mecklenburg-Vorpommern. Bei insgesamt 72 389 Einsätzen schafften sie jedoch auch einen Rekord: In 84 Prozent der Fälle konnten die Autofahrer mit dem Wagen weiterfahren.

ZIB-Project Hyperthermia

- Discovery of the location tumors (cancer zones).
- Positioning of antennas for radiation therapy
- Computation of the strength of the radiation and “ray tracing” to discover the heat distribution in the body
- Concentrating the heat in the tumor
- Visualization



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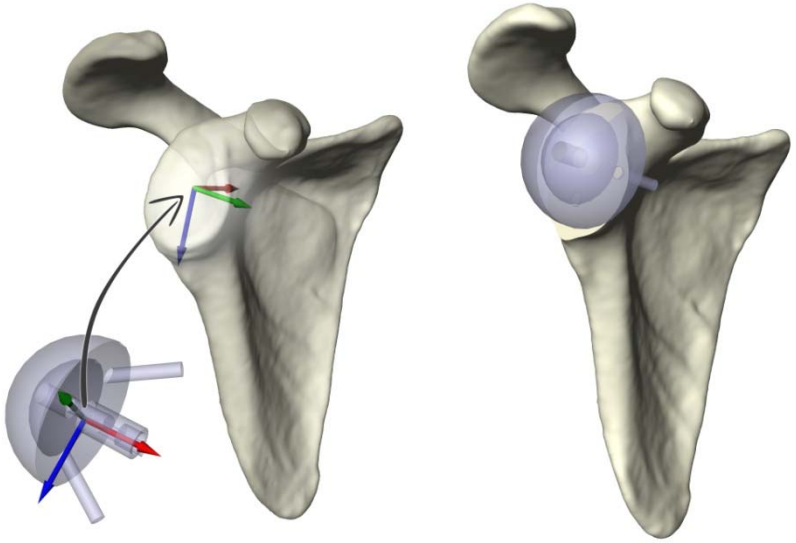
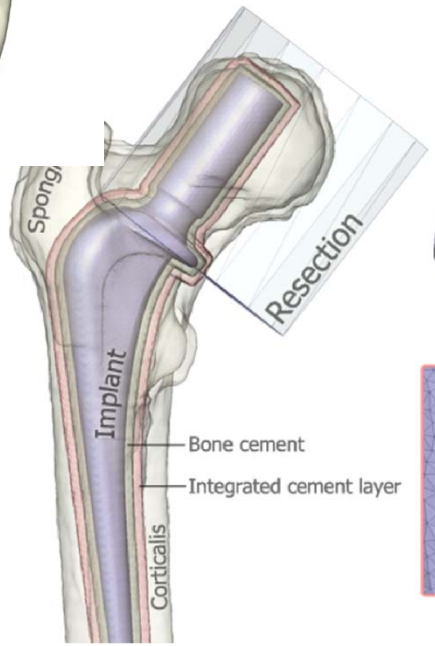
ZIB-Project Hyperthermia (Deuflhard group)

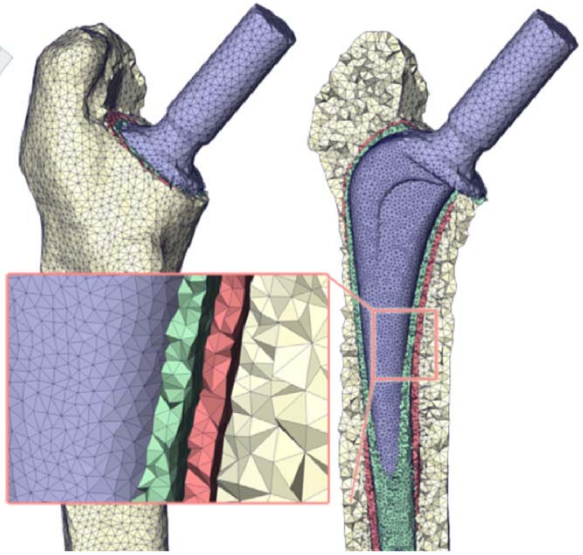
Implantation & Automatic FE-Mesh Generation



Virtual Implantation

- Extraction of joint coordinate systems
- Automatic implant selection and positioning



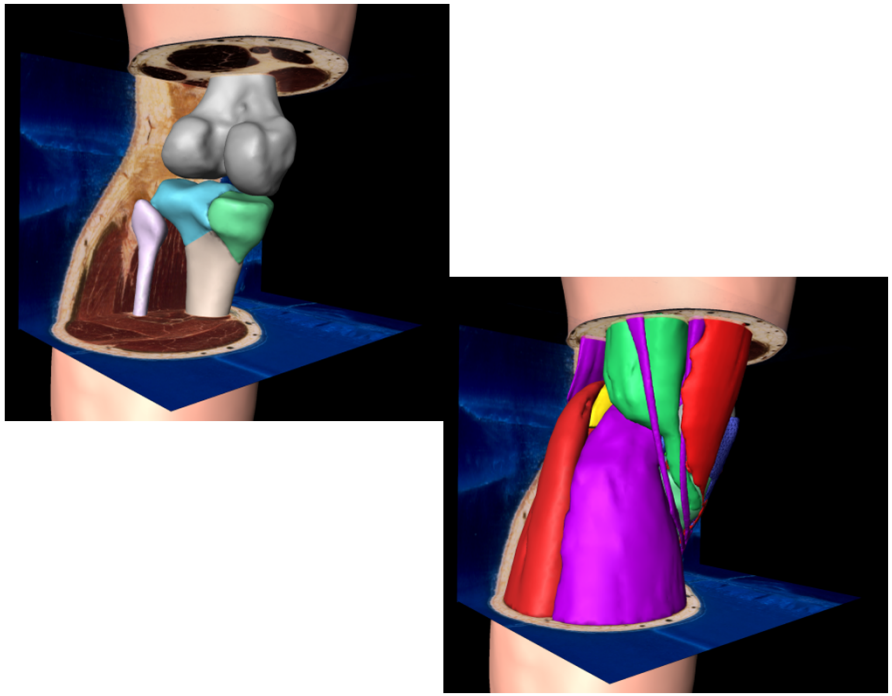


FE-mesh generation

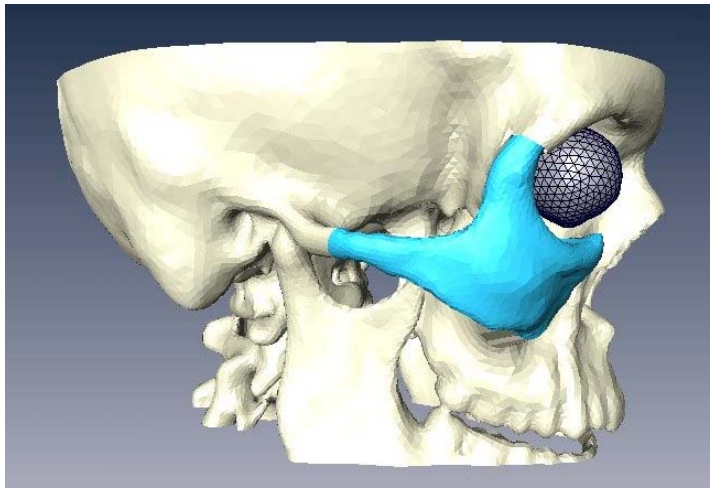
- Feature-preserving, multi-material tetrahedral meshes
- Large scale studies
- Delaunay grid

MATHEON A17
Computational Surgery Planning

Moving joints



Bone implant design

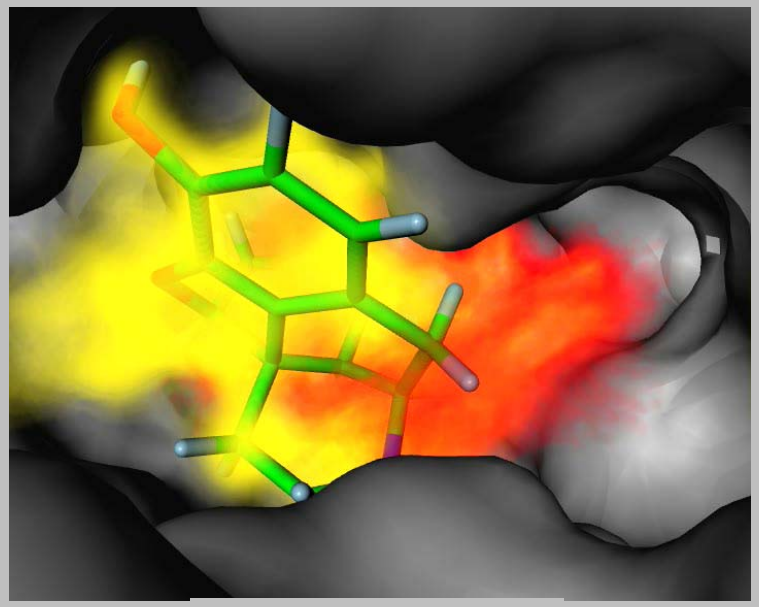


State constrained optimization, biomechanical modelling, dynamical contact problems

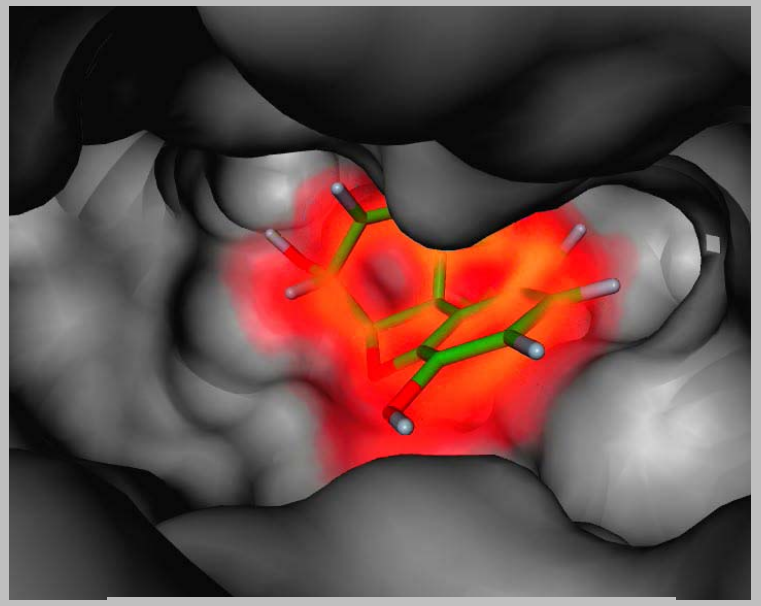
Application Area A – Life Sciences

Novel Pain Relief Drugs

Selective pain relief drug in binding pocket of μ-opioide receptor



inactive in CNS



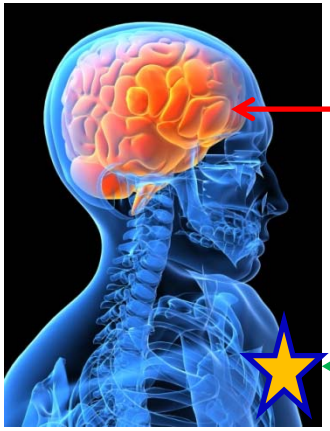
active in inflamed tissue

molConcept

novel in silico design strategy
two patents
ongoing clinical tests

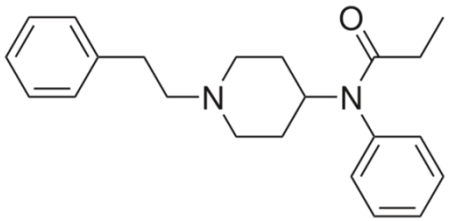
CHARITÉ

Pain relief drugs: opioids



side effects
respiratory depression
constipation, tolerance,
addiction…

pain relief effect



Opioid Fentanyl (Fen),
EUR 271 Mio. p.a. in Germany
EUR 4 Mrd p.a. world-wide (mainly USA)


CMAJ COMMENTARY

Deaths related to the use of prescription opioids

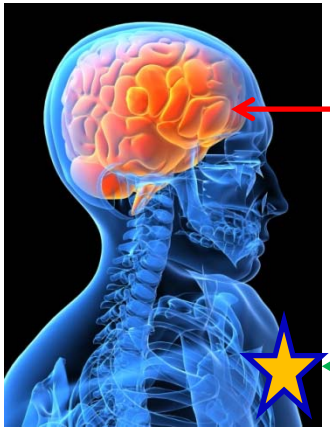
Benedikt Fischer PhD, Jürgen Rehm PhD

…prescription pharmaceuticals are now involved in more overdose deaths than either heroin or cocaine in North America

B. Fischer, J. Rehm
Deaths related to the use of prescription opioids
CMAJ. Dec 8, 2009; 181(12): 881–882.

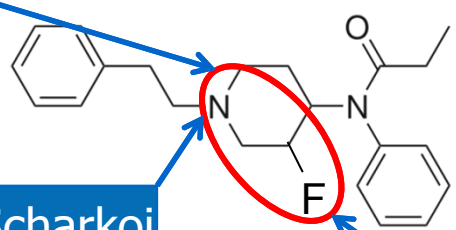
pH-dependent opioids tests: in vitro & vivo

Conformation dynamics & quantum chemistry



side effects
healthy tissue **pH 7**

pain relief effect
inflammation **pH 5**



O. Scharkoi

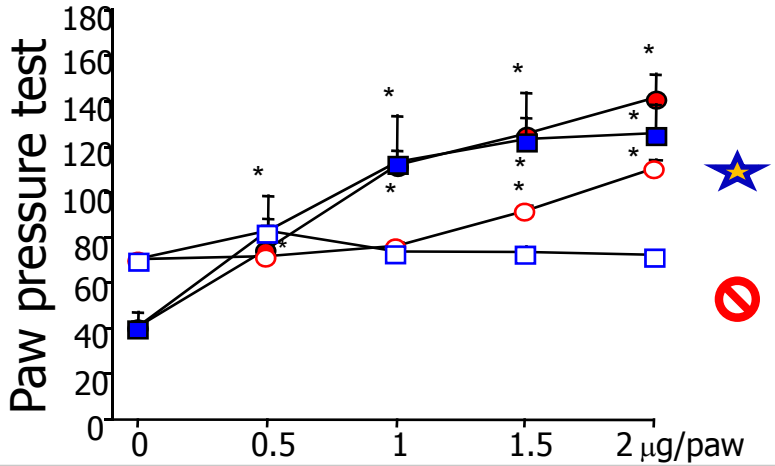
M. Weber

F-Fentanyl

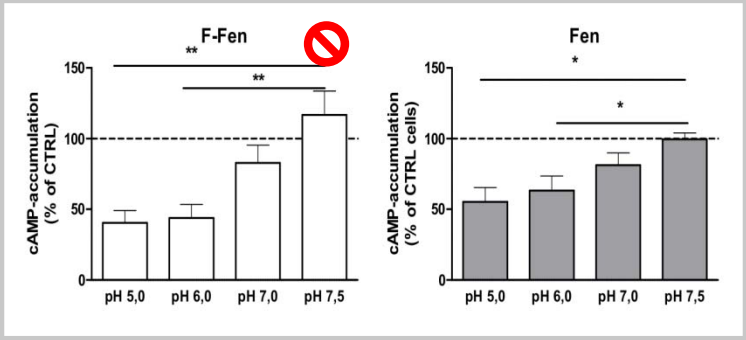
ZIB, Charité

in-vivo

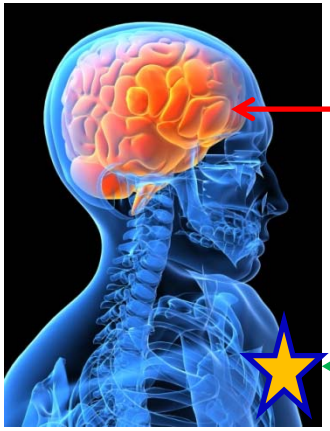
Injection into inflamed paw (i.pl.)



in-vitro

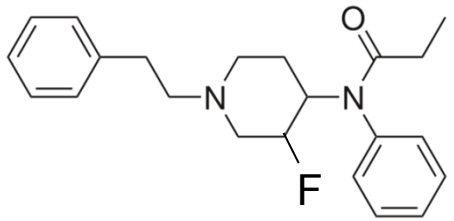


Pain relief drugs:patents



side effects
healthy tissue **pH 7**

pain relief effect
inflammation **pH 5**



F-Fentanyl

ZIB, Charité

Patents in nationalization phase (EU, USA) after PCT

C. Stein, C. Zöllner, M. Weber, O. Scharkoi: Fentanyl derivatives as pH-dependent opioid receptor agonists. EP2559685

C. Stein, M. Weber, O. Scharkoi, P. Deuflhard: Method and system for indentifying compounds that bind and preferably activate a target opioid receptor in a pH-dependent manner. EP2613277

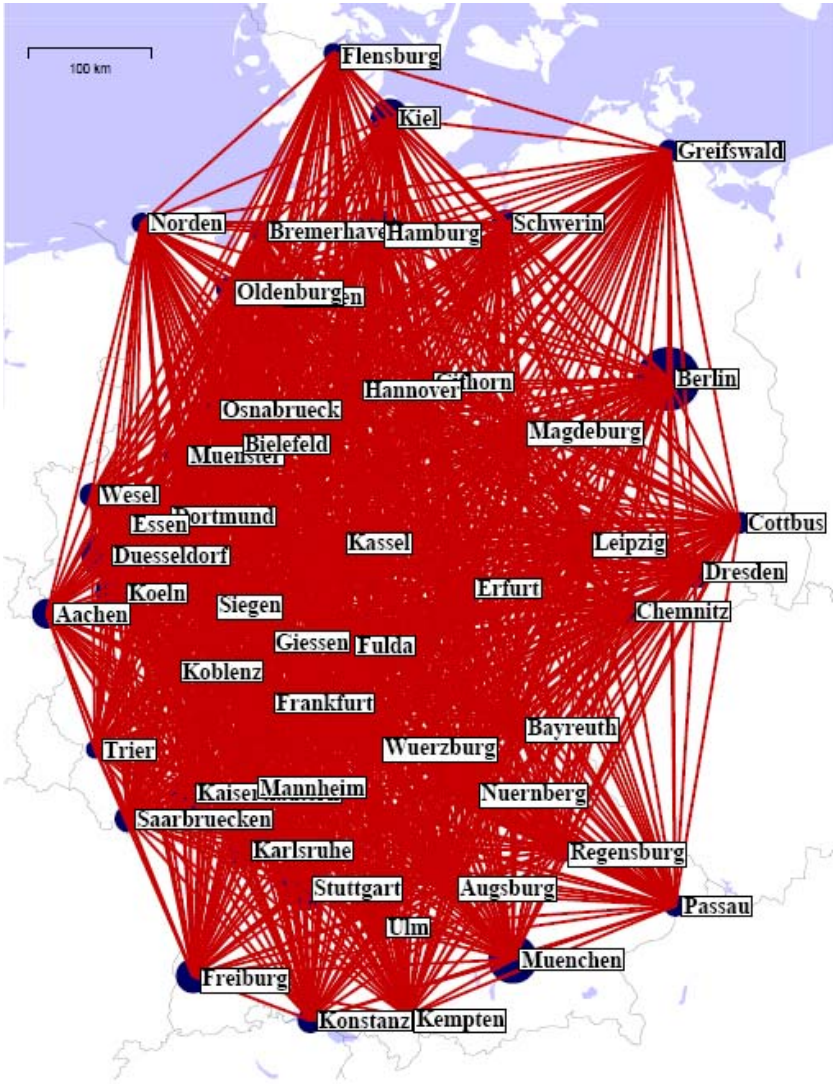
Estimated value (including risk to fail clinical phases): EUR 6,7 Mio

Visualization, Animation: Spider Man (spin-off mental images)

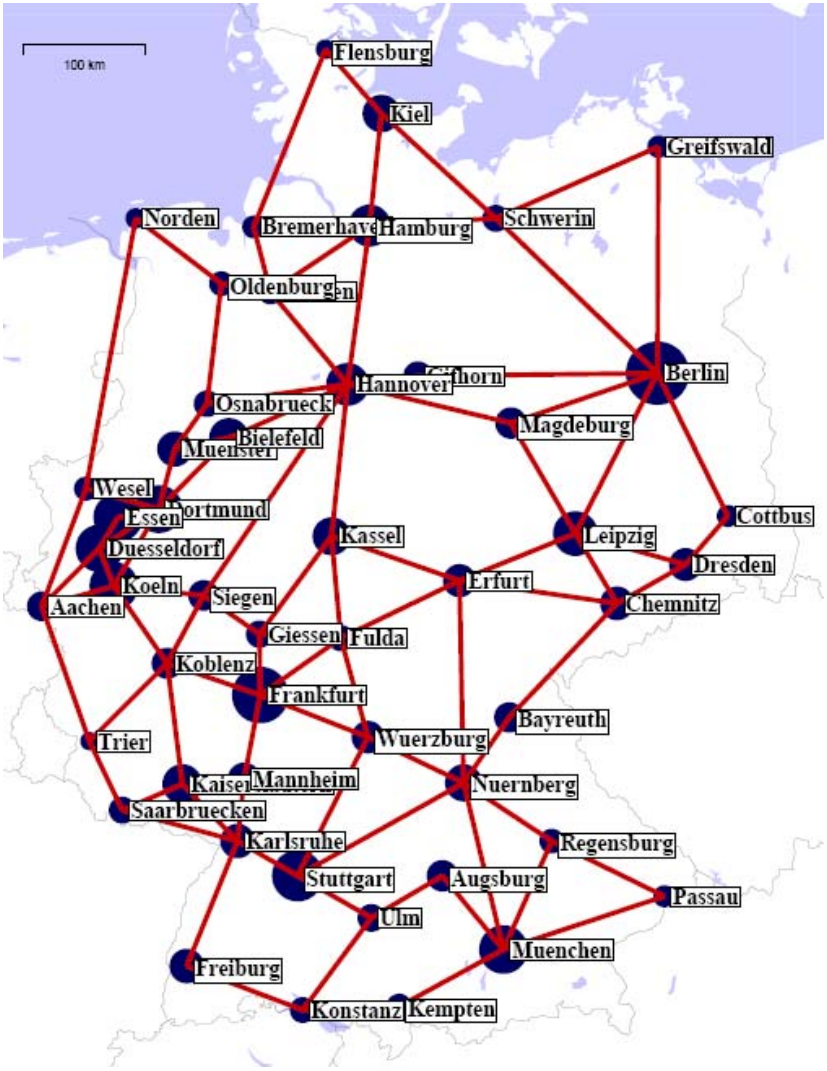
Martin Grötschel

Telecommunication network design
MATHEON B3

Logical connections

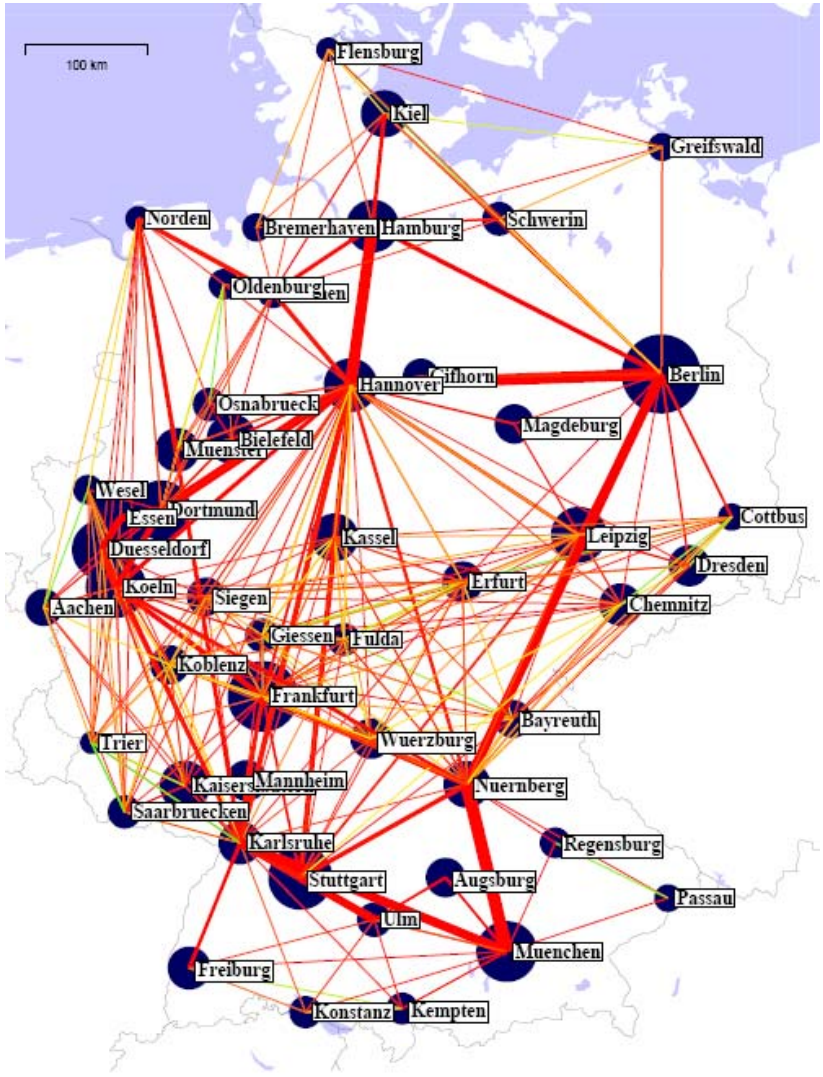


Physical connections

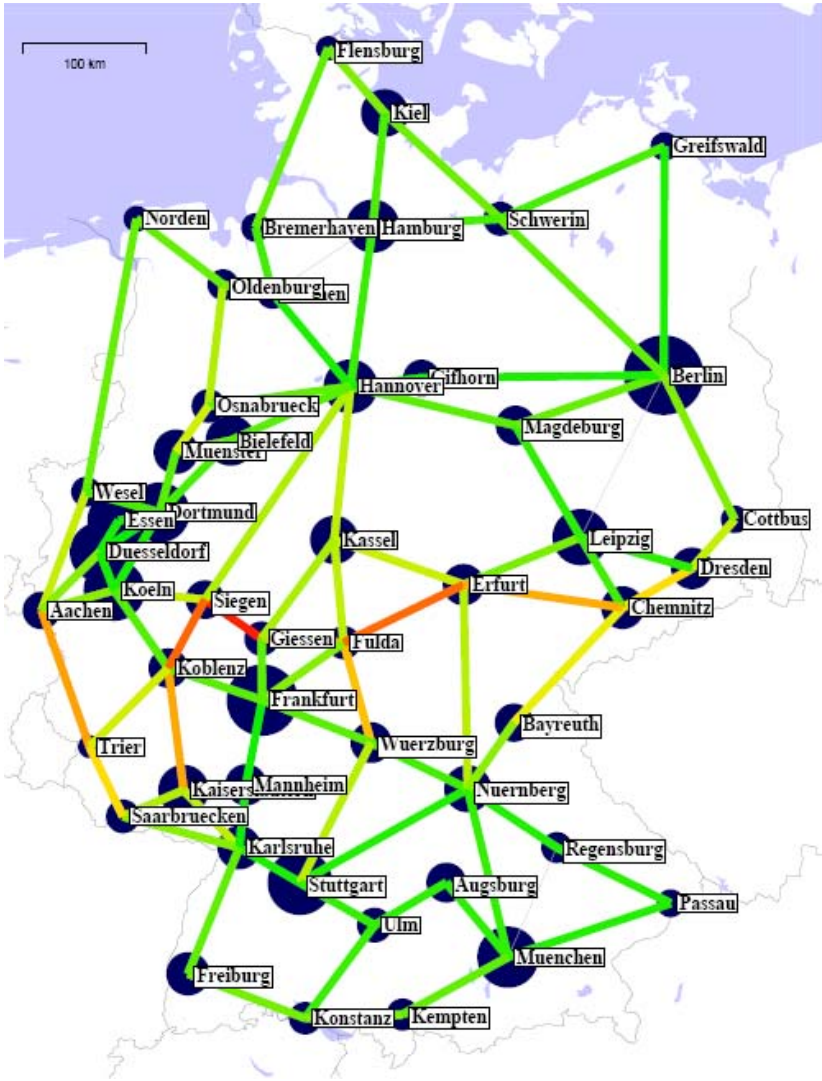


Network design
MATHEON B3

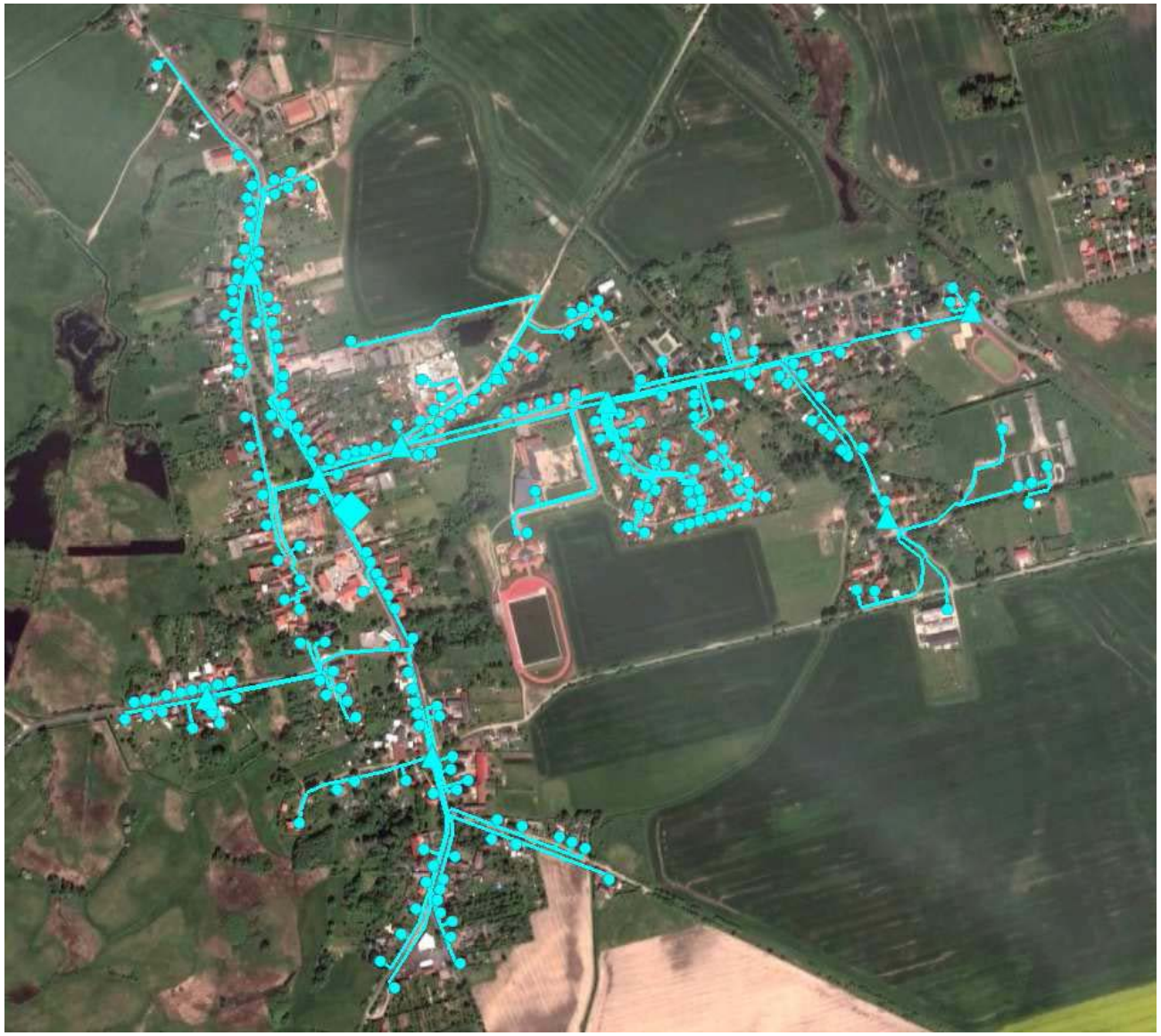
Logical connections: solution



Physical connections: solution



FTTH: Fiber To The Home



A Project with BHP Billiton

Production scheduling for an open pit mine with a stockpile

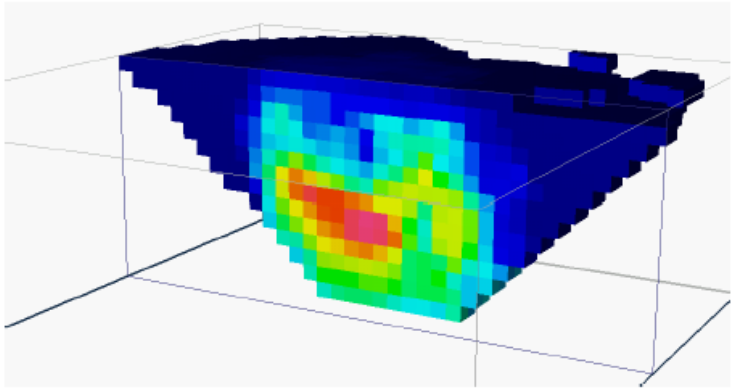
Goal Maximize net present value

Decisions

- Which block is mined when?
- What material is processed immediately?
- What material is stockpiled?
- What fraction of stockpile is processed when?

Constraints

- Block mining order
- Mining and processing capacities
- ***Mixing of material in stockpile***



Block model of an open pit mine
blue = low grade ore, red = high grade ore

Stockpiles at Yandi mine, Australia.

Cooperation

The University of Melbourne

University of New South Wales

BHP Billiton

Martin Grötschel

Applications

Areas with significant mathematics demand:

- Industrial production (control of CNC machines, assembly line optimization, robot control,…)
- Mining (Scheduling, rock damage and fracture models, …)
- Health care & medicine (support for operations, drug design,…)
- Energy (optimization of energy production and mix, unit commitment,…)
- Financial mathematics (modelling of risk,…)
- Infrastructure planning (public transport, water, street, gas,… networks, harbor design)
- Telecommunication (network design, channel assignment)
- Logistics & Traffic and Transport (vehicle circulation,....)
- Sports
- …

- I can go on forever.....

Contents

Modelling?

Martin
Grötschel

Mathematical models of integer/combinatorial optimization

- travelling salesman problem (the prototype problem)
- routing
- location
- set-packing, -partitioning, -covering
- cut problems (max and min)
- scheduling
- node and edge colouring
- shortest paths (with resource constraints)
- various flow problems
- general integer and mixed-integer programs
- etc.

Typical optimization problems

$$\max f(x) \ \ or \ \ \min f(x)$$
$$g_i(x) = 0, \quad i = 1,2,\ldots,k$$
$$h_j(x) \le 0, \quad j = 1,2,\ldots,m$$
$$x \in \mathbb{R}^n \ (and \ \ x \in S)$$

„general“ (nonlinear) program NLP

$$\min c^T x$$
$$Ax = a$$
$$Bx \le b$$
$$x \ge 0$$

linear program LP

$$\min c^T x$$
$$Ax = a$$
$$Bx \le b$$
$$x \ge 0$$
$$x \in \mathbb{Z}^n$$
$$(x \in \{0,1\}^n)$$

(linear) integer program IP, MIP

program = optimization problem



Martin Grötschel

Industry requirements grow

$$\max f(x) \quad or \quad \min f(x)$$
$$g_i(x) = 0, \quad i = 1, 2, \ldots, \mathrm{p}$$
$$h_j(x) \leq 0, \quad j = 1, 2, \ldots, \mathrm{q}$$
$$x_i \in \mathbb{Z} \qquad for\ some\ i$$
$$x_j \in \{0,1\} \quad for\ some\ j$$
$$x_k \in \mathbb{R}^n \qquad for\ some\ k$$

More general:
mixed-integer nonlinear program
MINLP

Plus:

Stochastic aspects

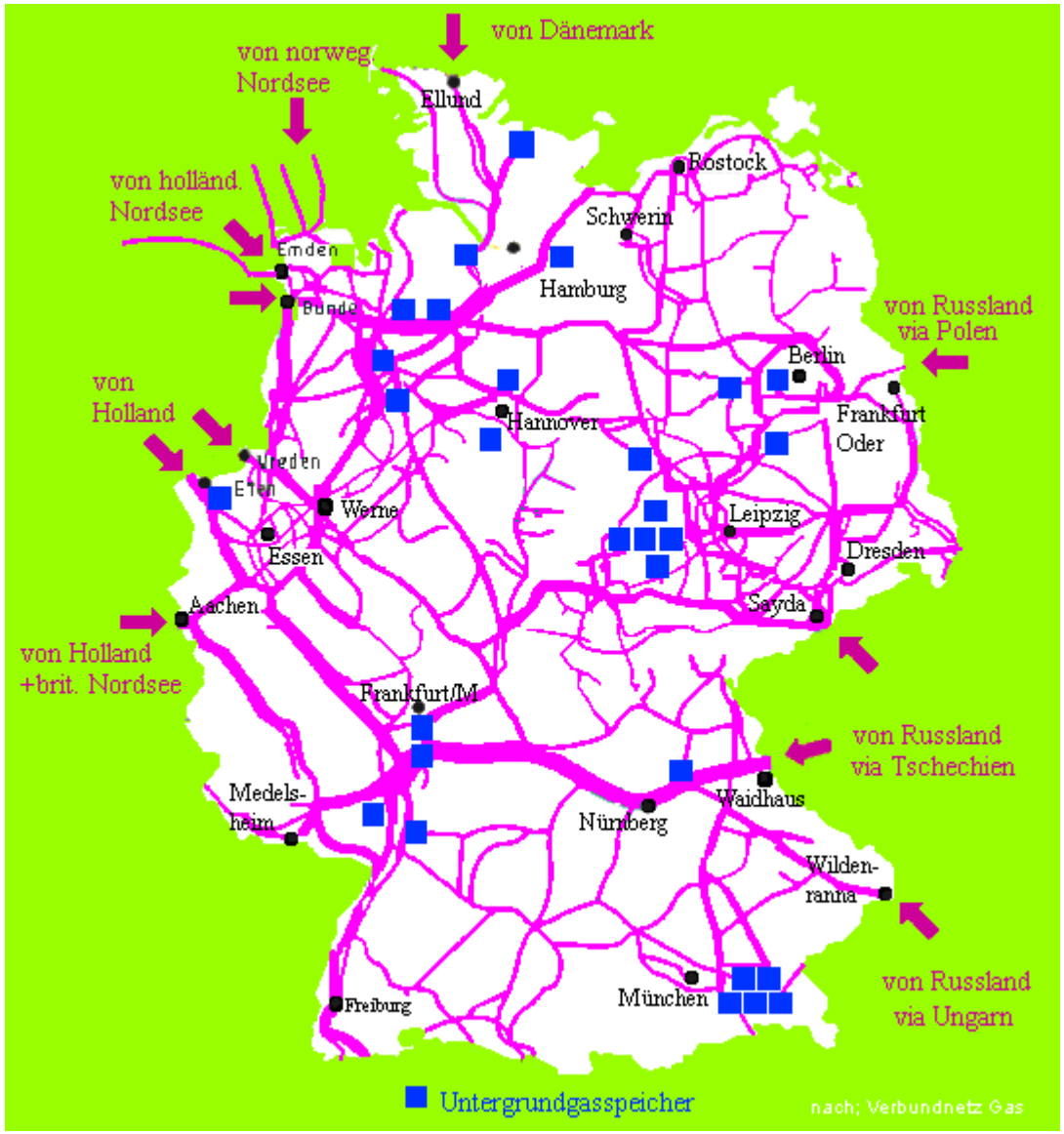
Robust optimization

Real time/online optimization

Several objectives

Example:
gas pipeline optimization

Simulating, Optimizing, Extension Planning of a Gas Pipeline Network



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MATHEON B20 &FORNE Project: Optimization of Gas Transport

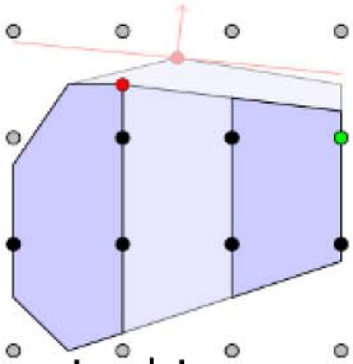
new challenges by E.ON Gastransport and the Bundesnetzagentur:

network configuration

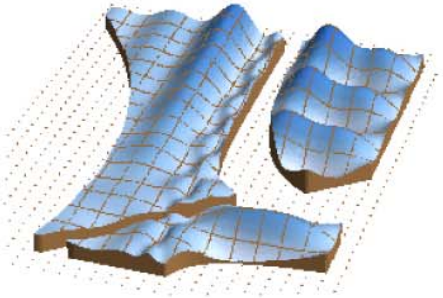
properties of gas

legal requirements

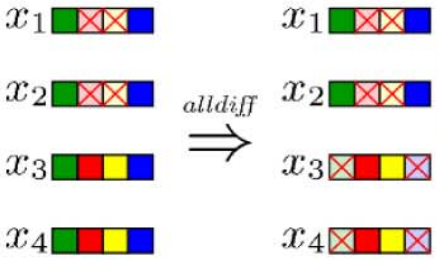
uncertain demand



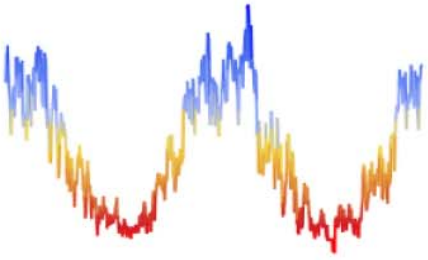
mixed-integer programming



nonlinear programming



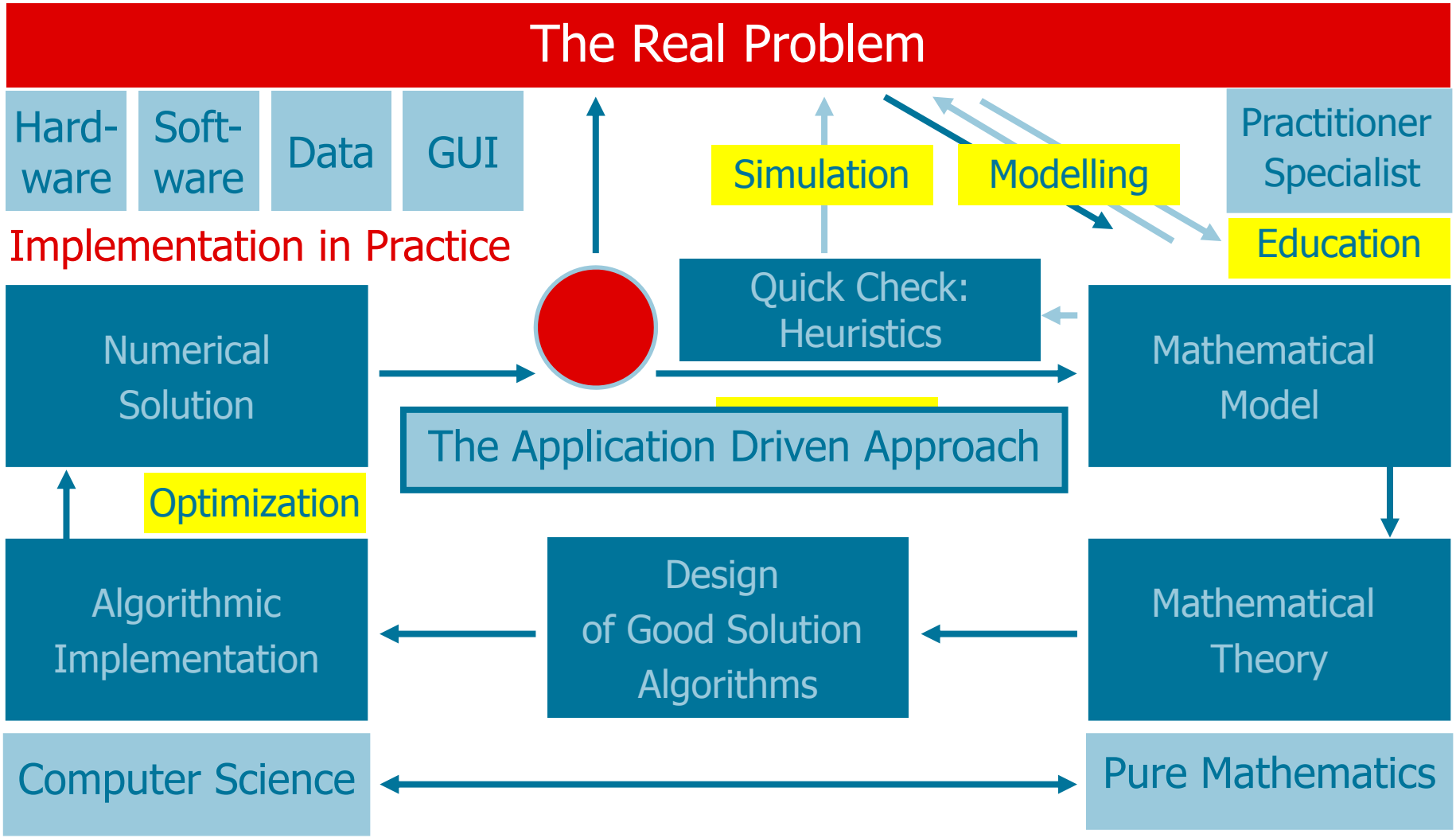
constraint programming



stochastic programming

Contents

The problem solving cycle in modern applied mathematics



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$$h_j(x) \le 0, \quad j = 1,2,\ldots,m$$
$$x \in \mathbb{R}^n \ (and \ \ x \in S)$$

„general“
(nonlinear)
program
NLP

$$\min c^T x$$
$$Ax = a$$
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$$x \ge 0$$

linear
program
LP

$$\min c^T x$$
$$Ax = a$$
$$Bx \le b$$
$$x \ge 0$$
$$x \in \mathbb{Z}^n$$
$$(x \in \{0,1\}^n)$$

(linear)
integer
program
IP, MIP

program = optimization problem



Progress in LP: 1988—2004

Operations Research,
Jan 2002, pp. 3—15, updated in 2004)

Courtesy Bob Bixby

- Algorithms (*machine independent*):

  Primal *versus* best of Primal/Dual/Barrier 3,300x
- Machines (workstations →PCs): 1,600x
- NET: Algorithm × Machine 5,300,000x

(2 months/5300000 ~= 1 second)


SoPlex sequential object-oriented simplex

SoPlex is an implementation of the revised simplex algorithm. It features primal and dual solving routines for linear programs and is implemented as a C++ class library that can be used with other programs.

Roland Wunderling,
Paralleler und Objektorientierter Simplex-Algorithmus,
Dissertation, TU Berlin,1997

now employed by IBM, developing CPLEX's LP technology

Zimpl

Zimpl is a little language to translate the mathematical model of a problem into a linear or (mixed-) integer mathematical program expressed in .lp or .mps file format which can be read and (hopefully) solved by a LP or MIP solver.

- Thorsten Koch, *Rapid Mathematical Programming*, Dissertation, TU Berlin 2004
  (awarded with the Dissertation Prize 2005 of the Gesellschaft für Operations Research)

SCIP http://scip.zib.de/

Tobias Achterberg, Tobias, *Constraint Integer Programming*, Dissertation, TU Berlin, 2007

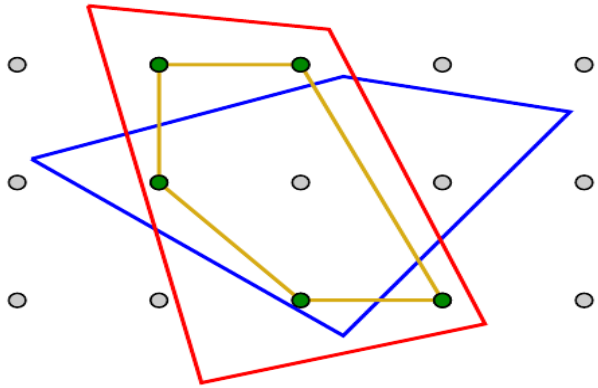
- Dissertation Prize 2008 of the Gesellschaft für Operations Research (GOR)
- George B. Dantzig Dissertation Award 2008 of the Institute of Operations Research and the Management Sciences (INFORMS), 2nd prize)
- Beale-Orchard-Hays Prize 2009 of the Mathematical Optimization Society for the paper: Tobias Achterberg, "SCIP: Solving constraint integer programs", Mathematical Programming Computation, 1 (2009), pp. 1-41.
- Started is "business career" at ILOG developing CPLEX's MIP technology, moved to IBM when ILOG was acquired by IBM, and is now with Gurobi.

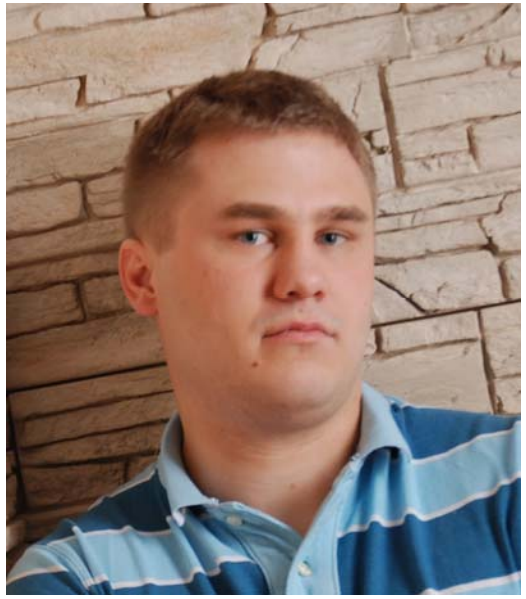
GCG Generic Column Generation

GCG extends the branch-cut-and-price framework SCIP to a generic branch-cut-and-price solver.

- performs Dantzig-Wolfe decomposition for detected or provided structure
- Solves reformulation with branch-and-price approach
- pricing problems solved as MIPs
- generic branching rules for branch-and-price

Provides easy access to another state-of-the-art MIP solving technology.





Gerald Gamrath

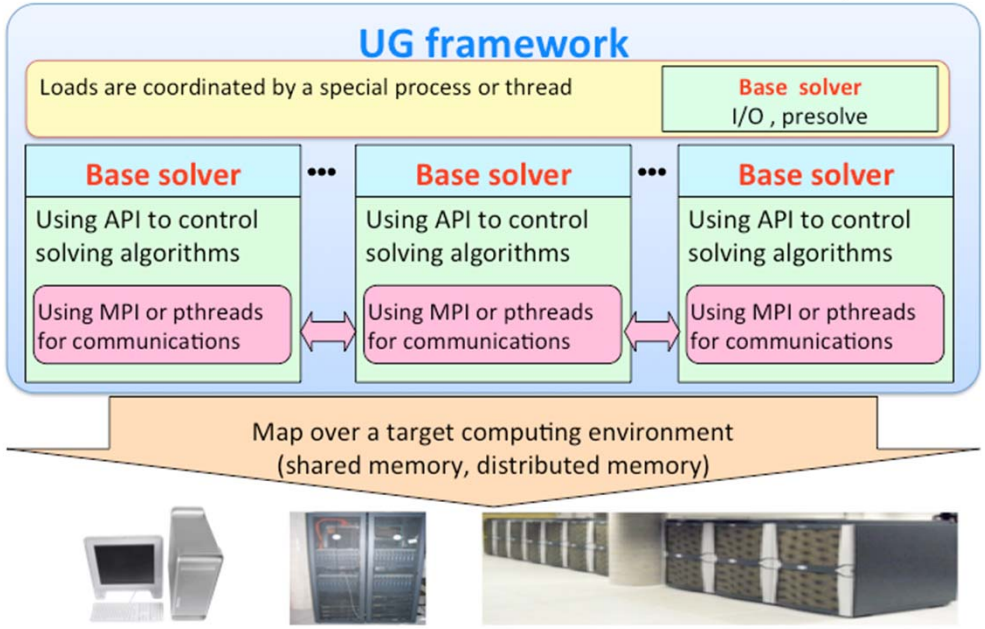
Generic Branch-Cut-and-Price, Diploma Thesis, TU Berlin, 2010

Currently developed in cooperation with RWTH Aachen, also funded by SPP 1307

UG Ubiquity Generator Framework

UG is a generic framework to parallelize branch-and-bound based solvers (e.g., MIP, MINLP, ExactIP) in a distributed or shared memory computing environment.

- Exploits powerful performance of state-of-the-art "base solvers", such as SCIP, CPLEX, etc.
- Without the need for base solver parallelization



Yuji Shinano,
A Generalized Utility for Parallel Branch-and-Bound Algorithmus,
Dissertation, Tokyo University of Science,1997

The travelling salesman problem

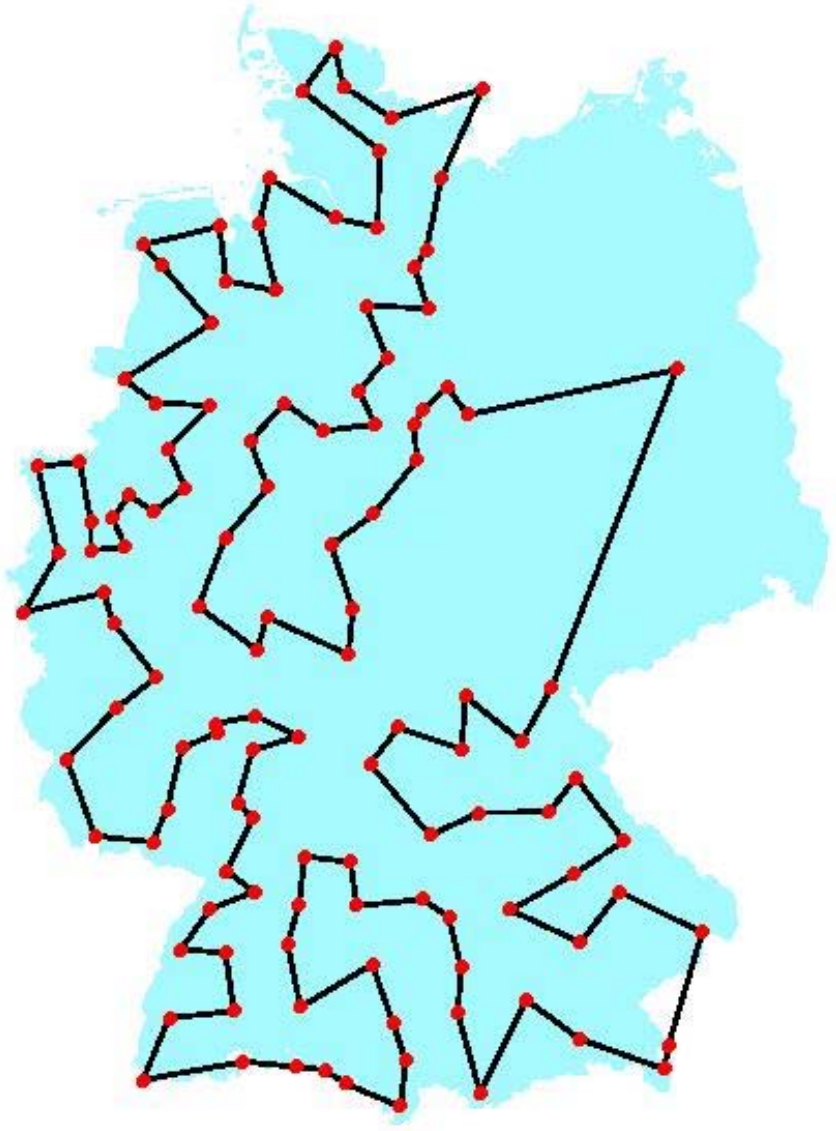
Given n „cities“ and „distances“ between them. Find a tour (roundtrip) through all cities visiting every city exactly once such that the sum of all distances travelled is as small as possible. (TSP)

The TSP is called symmetric (STSP) if, for every pair of cities i and j, the distance from i to j is the same as the one from j to i, otherwise the problem is called aysmmetric (ATSP).



Martin
Grötschel

West-Germany and Berlin



120 cities
7140 variables

1975

M. Grötschel

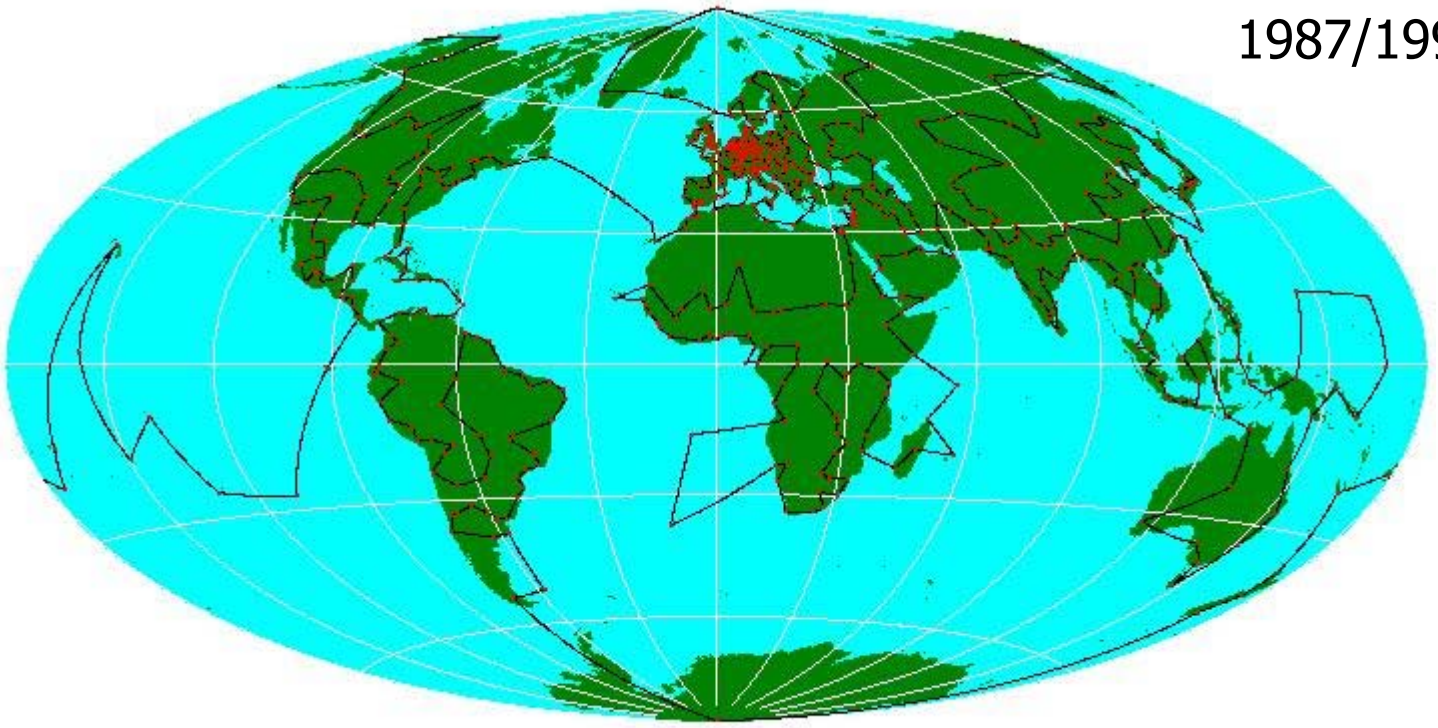
Martin Grötschel

A trip around the world

666 cities

221,445 variables

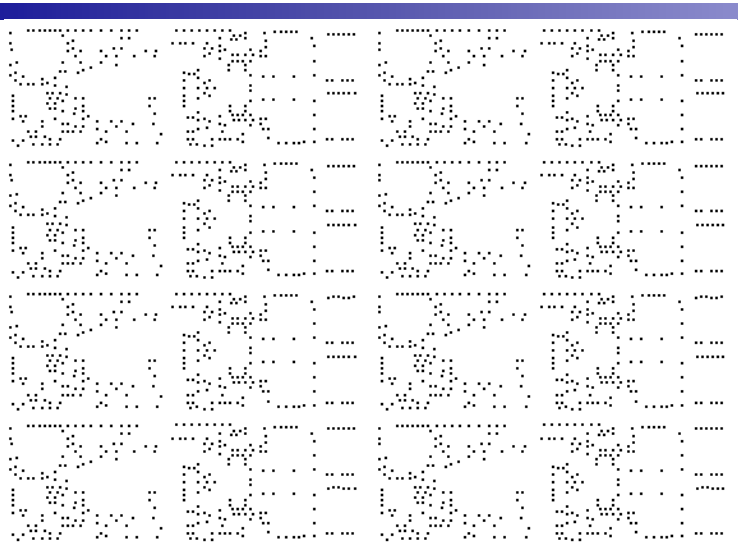
1987/1991



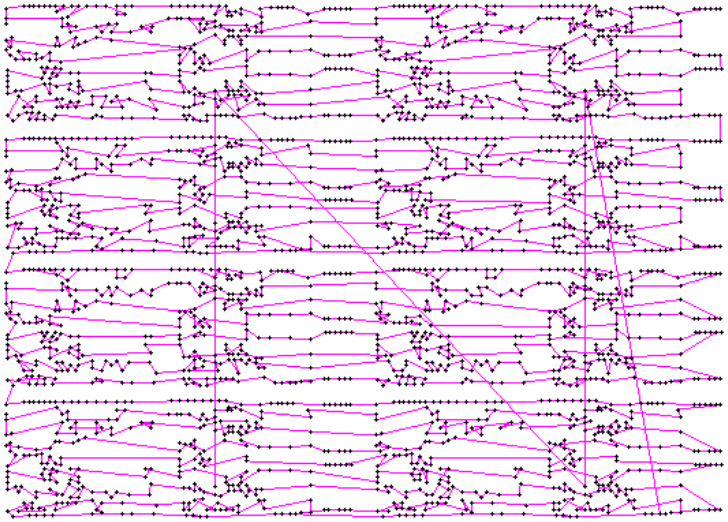
M. Grötschel, O. Holland

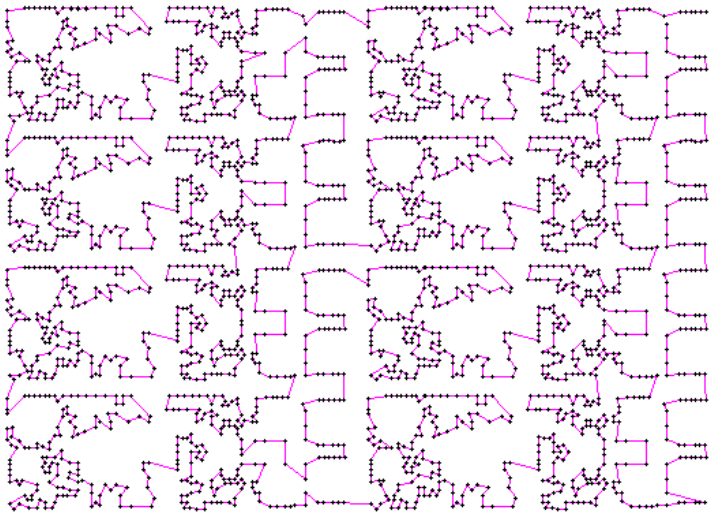
Martin Grötschel

Drilling 2103 holes into a PCB



Significant Improvements
via TSP





industry solution

optimal solution

Martin
Grötschel

Some TSP World Records

2006
pla 85,900
solved

3,646,412,050
variables

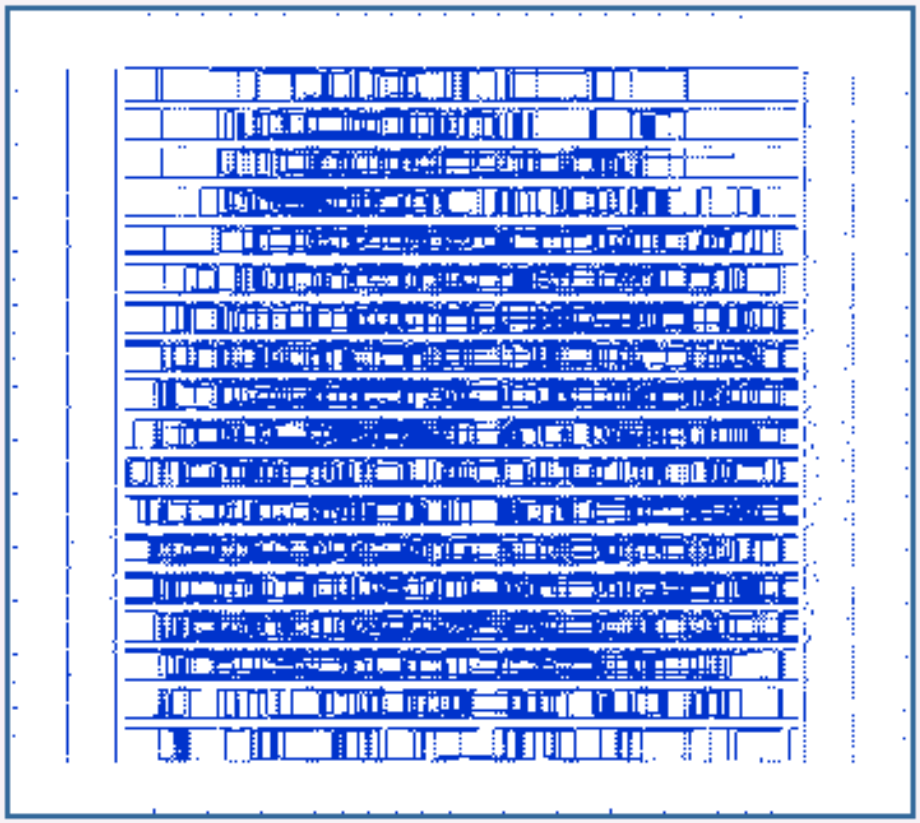
number of cities
2000x
increase

4,000,000
times
problem size
increase

in 52
years

year	authors	# cities	# variables
1954	DFJ	42/49	820/1146
1977	G	120	7140
1987	PR	532	141,246
1988	GH	666	221,445
1991	PR	2,392	2,859,636
1992	ABCC	3,038	4,613,203
1994	ABCC	7,397	27,354,106
1998	ABCC	13,509	91,239,786
2001	ABCC	15,112	114,178,716
2004	ABCC	24,978	311,937,753
2005 W. Cook, D. Epsinoza, M. Goycoolea		33,810	571,541,145

The current world record



85,900 Locations in a VLSI Application
Solved in 2006

http://www.tsp.gatech.edu/optimal/index.html

http://www.tsp.gatech.edu/pla85900/index.html

Martin Grötschel

Contents

Public Transport Projects (ZIB and MATHEON)

Busses (Berlin and elsewhere)

- Telebus (Transportation of disabled persons)
- Bus Circulation
- Bus driver Scheduling
- Integrated Vehicle and Driver Scheduling
- Timetable Exchange

Subways and Light Railways

- Subway Time Tabling
- Vehicle Scheduling

Infrastructure Planning

- Line Planing
- Network Planning (Potsdam)
- Fare Planing

Airlines

- Airline Crew Scheduling
- Tail Assignment: Robustness

Railways

- Railway Track Allocation
- ICE Circulation

Spin-Offs : LBW, Intranetz

Solution "Technology"

- "good" mathematical modelling in cooperation with partners from practice
- linear programming
- integer and mixed-integer programming
- non-differentiable optimization
- lots of heuristics
- "verification" by simulation



BVG (Berlin): bus circulation

Systematisierter Einsatz

Die neuen Optimierungsmethoden, die die BVG jetzt nach und nach nutzen will, stammen vom Konrad-Zuse-Zentrum für Informationstechnik und garantieren nach Roß' Angaben Einsparungen von maximal 100 Millionen Mark im Jahr. „Sie sind nötig, um unser Angebot in dieser schweren Lage stabilisieren und dem Einsparungsdruck überhaupt standhalten zu können."

Bereits 1991 beauftragte die BVG die Berliner Software-Firma IVU, ein EDV-System zur Betriebsplanung zu entwikkeln. IVU steht für „Gesellschaft für Information, Verkehrs- und Umweltplanung GmbH", ein Unternehmen mit 120 Mitarbeitern, das auf Verkehrsplanung und Logistik spezialisiert ist. Der BVG ging es bei dem Auftrag vor allem darum, die Einsatzplanung ihrer Fahrzeuge zu systematisieren.

WISSENSCHAFT UND PRAXIS — Rheinischer Merkur — Nummer 39 · 26. September 1997 — 37

INFORMATIK / *Ein Lehrbeispiel, wie sich Mathematik und Wirtschaft ergänzen*

Auf Sparkurs zum Ziel

Das Berliner Busnetz kostet jährlich Millionen. Mit Hilfe moderner Software könnte man auf gewaltige Zuschüsse verzichten.

■ VASCO ALEXANDER SCHMIDT

Die Mathematik ist die Wissenschaft abstrakter Probleme. Deshalb erscheint sie so oft als weltabgewandte Spielerei. Doch das ist nur die halbe Wahrheit. Längst mischt sich die Mathematik in die Praxis ein. Überall, wo in der Wirtschaft gespart und verbessert werden muß, kann sie helfen. Professor Martin Grötschel, Vizepräsident des Konrad-Zuse-Zentrums für Informationstechnik in Berlin, steht für das neue Selbstbewußtsein der angewandten Mathematik. Er ist Experte für die kombinatorische Optimierung. Seine Botschaft: „Wer heute die großen Verkehrsnetze und komplizierten Fabriken optimieren will, muß sich mit Mathematik beschäftigen, um unnötige Kosten zu vermeiden."

Nun gibt es in Berlin ein Lehrbeispiel, wie Mathematik und Wirtschaft zueinanderkommen können. Die Berliner Verkehrsbetriebe (BVG) haben vor wenigen Wochen begonnen, die Einsatzplanung ihrer Fahrzeuge zu verbessern. Bisher wurden die Pläne, wenn auch mit Computerhilfe, per Hand erstellt. Von einer kostengünstigen Planung war man weit entfernt.

Um ihre Kosten zu decken, hat die BVG Jahr für Jahr große Zuschüsse vom Berliner Senat bekommen. Doch damit ist nun Schluß: dem Land Berlin geht das Geld aus, so daß auch die BVG unter einem enormen Sparzwang steht. „Wir müssen jährlich dreistellige Millionenbeträge einsparen", erklärt Jürgen Roß, Planungsingenieur bei der BVG. „Bis zum Jahr 2000 können wir von den heute rund 20 000 Mitarbeitern nur noch 15 000 beschäftigen."

Systematisierter Einsatz

Die neuen Optimierungsmethoden, die die BVG jetzt nach und nach nutzen will, stammen vom Konrad-Zuse-Zentrum für Informationstechnik und garantieren nach Roß' Angaben Einsparungen von maximal 100 Millionen Mark im Jahr. „Sie sind nötig, um unser Angebot in dieser schweren Lage stabilisieren und dem Einsparungsdruck überhaupt standhalten zu können."

Bereits 1991 beauftragte die BVG die Berliner Software-Firma IVU, ein EDV-System zur Betriebsplanung zu entwikkeln. IVU steht für „Gesellschaft für Information, Verkehrs- und Umweltplanung GmbH", ein Unternehmen mit 120 Mitarbeitern, das auf Verkehrsplanung und Logistik spezialisiert ist. Der BVG ging es bei dem Auftrag vor allem darum, die Einsatzplanung ihrer Fahrzeuge zu systematisieren.

schnell und komfortabel am Bildschirm erstellt werden können. Außerdem wollte man die Dienstpläne und die Fahrpläne, die an den über 10 000 U-, Straßenbahn- und Busbahnhöfen der Stadt aushängen, auf Knopfdruck und ohne Umwege über eine Druckerei im eigenen Haus produzieren. Nach und nach wurden diese Werkzeuge eingeführt. Das jetzt installierte Optimierungsmodul für die Umlaufplanung von Straßenbahnen und Bussen ist der bisher bedeutendste Schritt der Zusammenarbeit.

Komfortable Hilfe

Zwar werden in Deutschland für die Verkehrsplanung meist schon Computer eingesetzt; diese aber unterstützen die Planer oft nur als ein einfaches, wenn auch komfortables Hilfsmittel. Andere Verkehrsunternehmen, etwa die Hamburger Hochbahn AG, setzen Computer schon seit Ende der siebziger Jahre ein, um Näherungslösungen für optimale Pläne zu berechnen. Die Forscher am Konrad-Zuse-Zentrum konnten noch einen Schritt weiter gehen: Ihre Computer berechnen das Optimum der Kosteneinsparung nicht nur annähernd, sondern ganz exakt. Ein wissenschaftlicher Durchbruch.

Die mathematische Grundlage ihrer Rechner bildet eine komplexes Gleichungssystem, eine sogenannte Matrix, mit mehr als 100 000 Zeilen und 70 Millionen Spalten. Die Zahlen in der gigantischen Tabelle geben an, wie die Busse eingesetzt werden sollen. Die Größe der Matrix weist auf ungezählte Details hin, die beachtet werden müssen: Der Computer muß garantieren, daß jeder der rund 1800 BVG-Busse morgens sein Depot verläßt und nach Dienstschluß dort wieder landet.

Es gibt Eindecker, Doppeldecker, Gelenk- und Minibusse, aber nicht jeder Bustyp kann jede Route bedienen. Außerdem sind komplizierte betriebliche und rechtliche Bedingungen zu beachten, etwa Pausenregelungen. Ziel ist es, die einzelnen Busfahrten so zu verketten, daß die Arbeitszeit der Fahrer gut ausgenutzt wird und die Leerfahrten von einem Einsatzort zum nächsten möglichst kurz sind. Alle diese Zielvorgaben stecken in der riesigen Matrix, die die Mathematiker „ganzzahliges lineares Programm" nennen. Ein lineares Programm ist für Mathematiker eine alltägliche Struktur. Sie taucht bei fast allen Fragen nach optimalen Mischverhältnissen, bei Güterflüssen in einer Fabrik und auch bei Stundenplänen auf.

Bildlich gesprochen besteht das Problem – in seiner einfachsten Form – aus einem Vieleck in der Ebene und einer Geraden, die durch das Vieleck verläuft. Nun verschiebt man die Gerade nach rechts. Ziel ist es, den letzten Punkt des Vielecks zu bestimmen, den die Gerade bei diesem Verschiebe-Prozeß gerade noch berührt. Hier liegt die kostengünstigste Lösung des Optimierungsproblems. Das Vieleck bei den Bus-Umlaufplänen ist sehr viel komplexer, man sollte es sich eher als einen verwinkelten Kristall mit mehreren Billionen Ecken und Kanten vorstellen.

„Eigentlich ist die Matrix für die Umlaufplanung bei der BVG so groß, daß man sie noch nicht einmal vollständig im Computer speichern könnte", verrät Andreas Löbel, Wissenschaftlicher Mitarbeiter von Martin Grötschel. „Pro Spalte gibt es aber nur drei Einträge, die von Null verschieden sind." Das bedeutet, daß sich die Matrix stark vereinfachen läßt. Und genau diese Eigenschaft machen sich die Mathematiker zunutze. So versucht ihr Algorithmus zuerst mit einem Teil der Matrix zu operieren. Findet er für diesen kleinen Teil eine Lösung, so vergrößert er nach und nach das Problem, bis er eine Lösung für die gesamte Matrix gefunden hat.

Pfiffige Programme

Von der Mathematik spüren die Planer bei der BVG wenig. Nicht einmal Großrechner werden gebraucht – so pfiffig wurde das System programmiert. Je nach Teilproblem dauert die Bearbeitung wenige Stunden oder sogar nur Minuten. „Das System wurde gut aufgenommen, da die Planer in kürzester Zeit verschiedene Szenarien testen und vergleichen können", berichtet Uwe Strubbe, der als Projektleiter bei der IVU für die Entwicklung des fertigen Softwareprodukts zuständig ist.

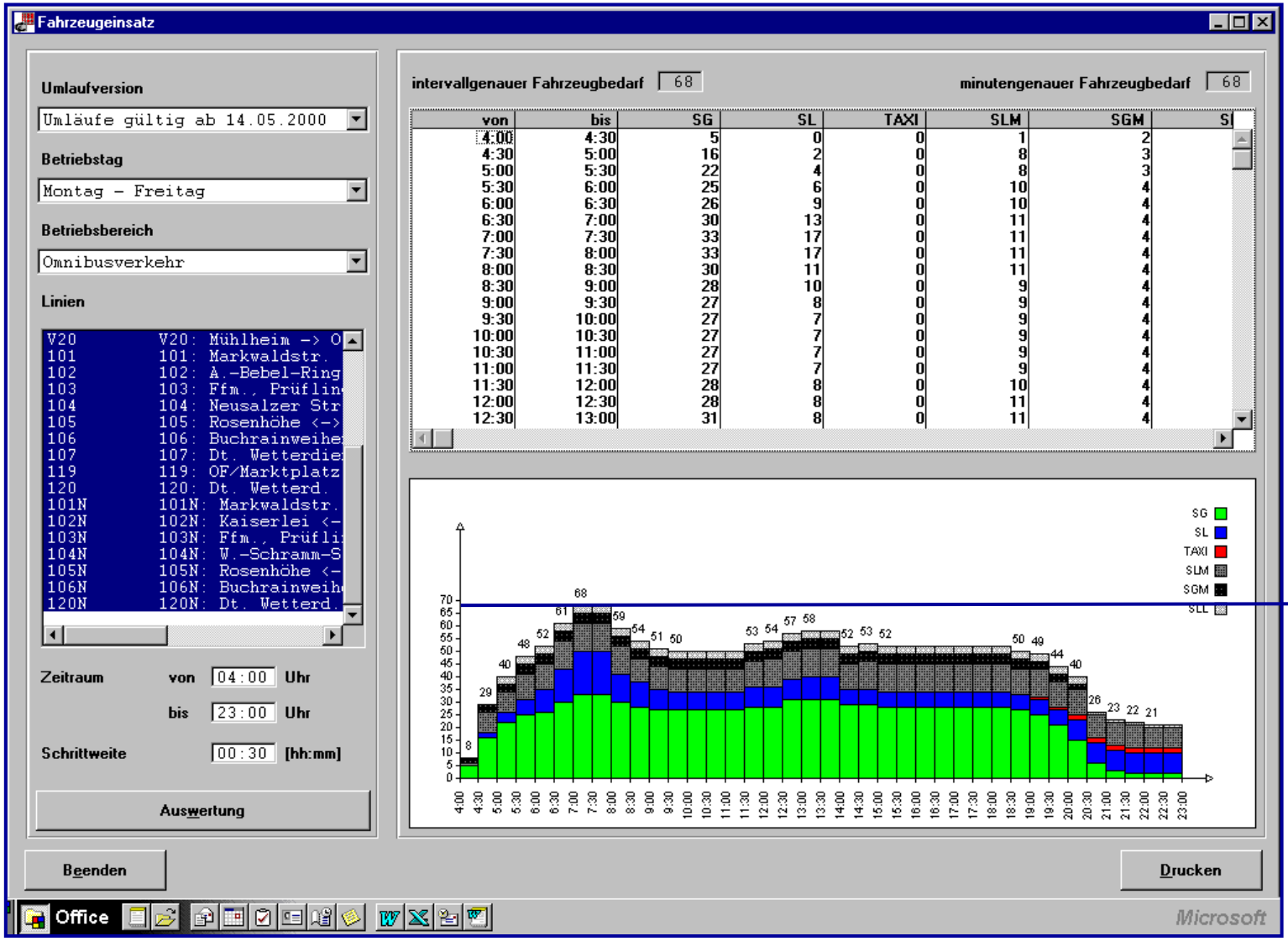
Auch Martin Grötschel betont den Nutzen für den Planer mehr als das Einsparungspotential: „Wir geben den Leuten Hilfsmittel in die Hand, die Kosten zu sparen: Ob dabei am Ende etwas eingespart oder der Service kostenneutral verbessert wird, ist nicht unsere, sondern eine politische Frage."

Die Politik freilich erwartet zur Zeit nur die größtmögliche Einsparung. In der Mathematik hat sie dafür ein passendes Instrument gefunden. □

ZAHLENWERK: *Nicht nur die Fahrpläne der Busse, sondern auch Dienst- und Einsatzpläne lassen sich programmieren.* foto: bonn-sequenz

Martin Grötschel

Vehicle Scheduling: The "Camel Curve"



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Savings in Berlin public transport

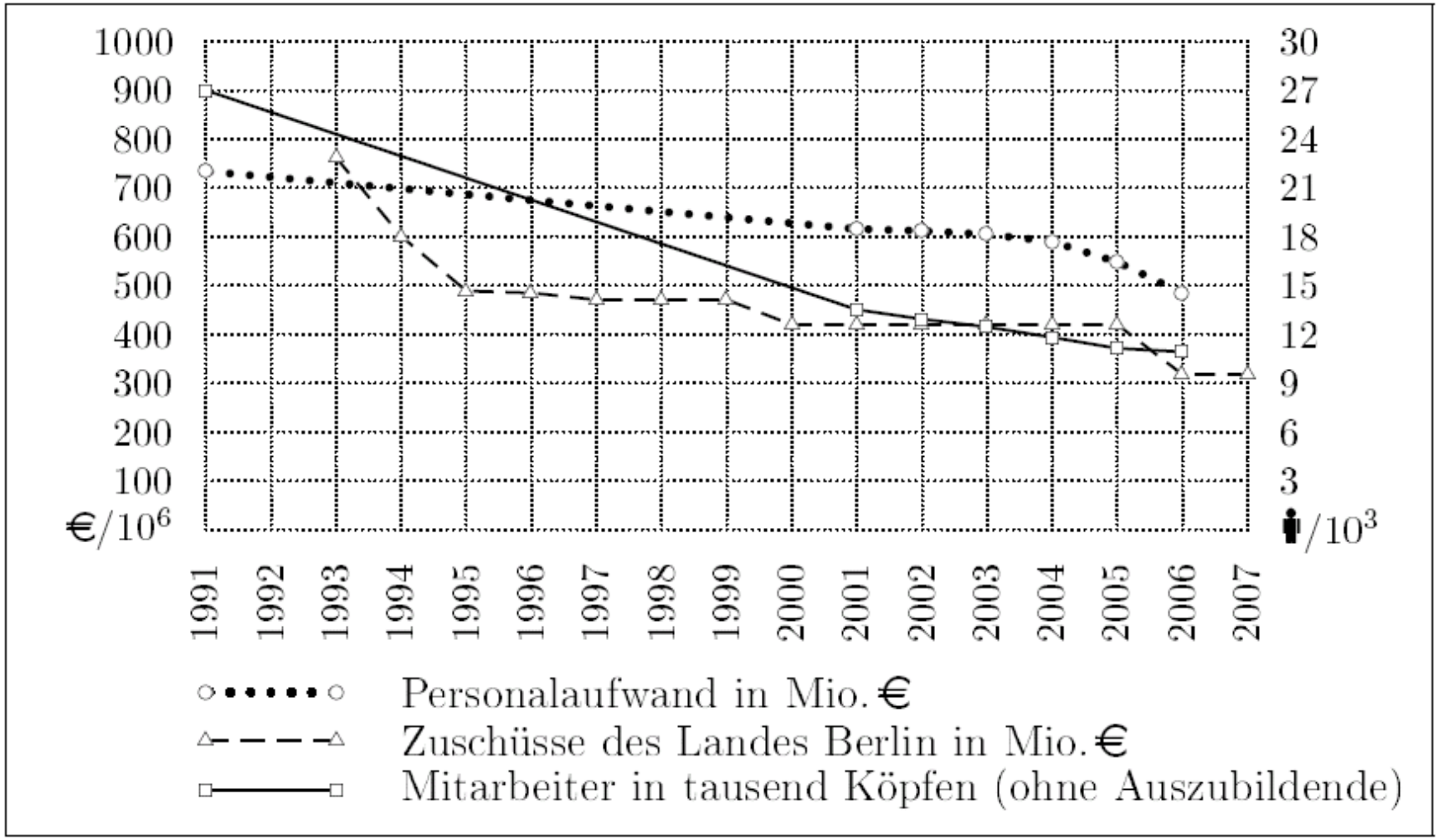
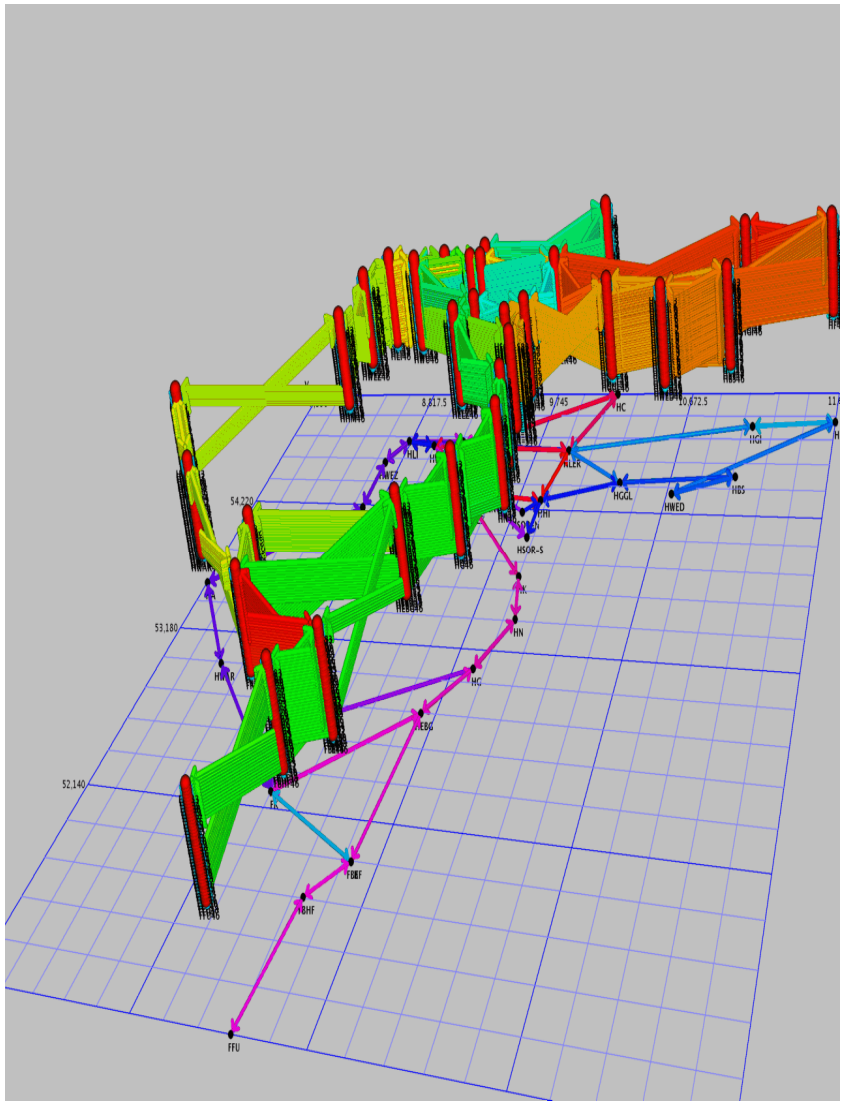
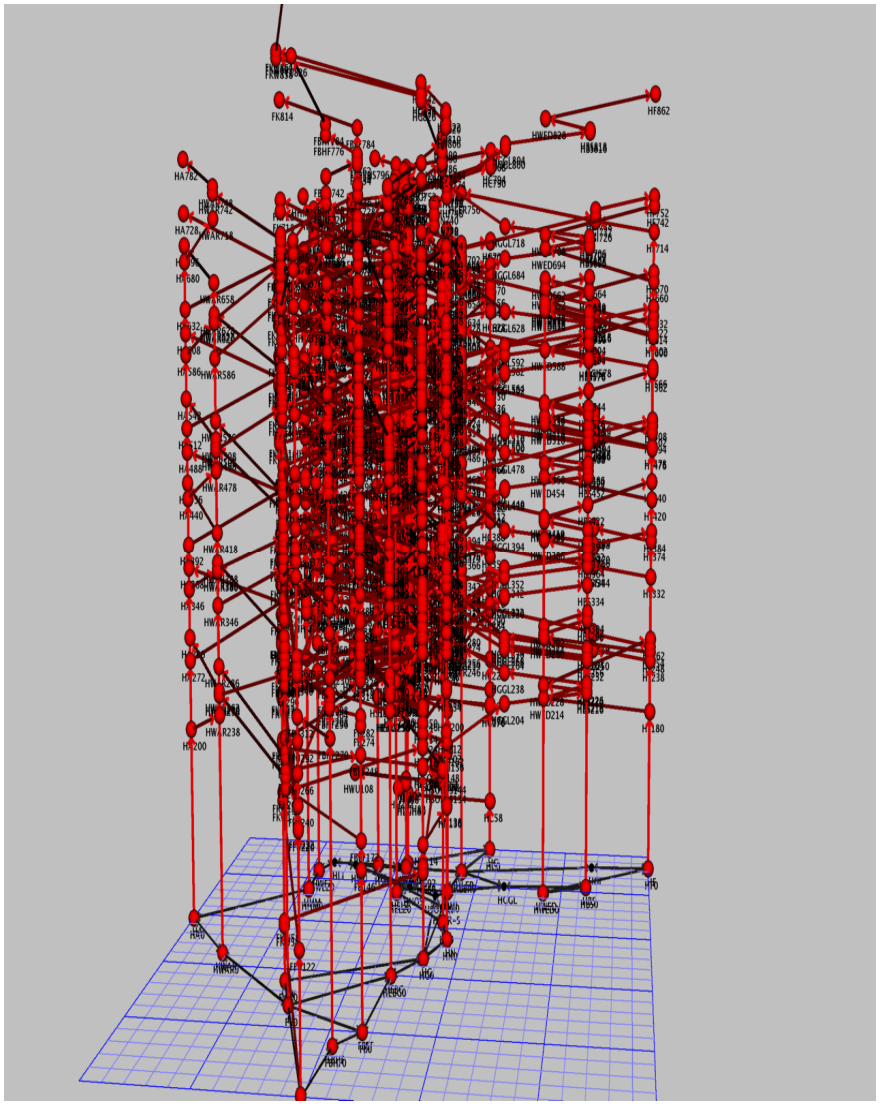


Abb. 3: Die Berliner Verkehrsbetriebe in Zahlen; Quelle: [36].

Railway Track Scheduling





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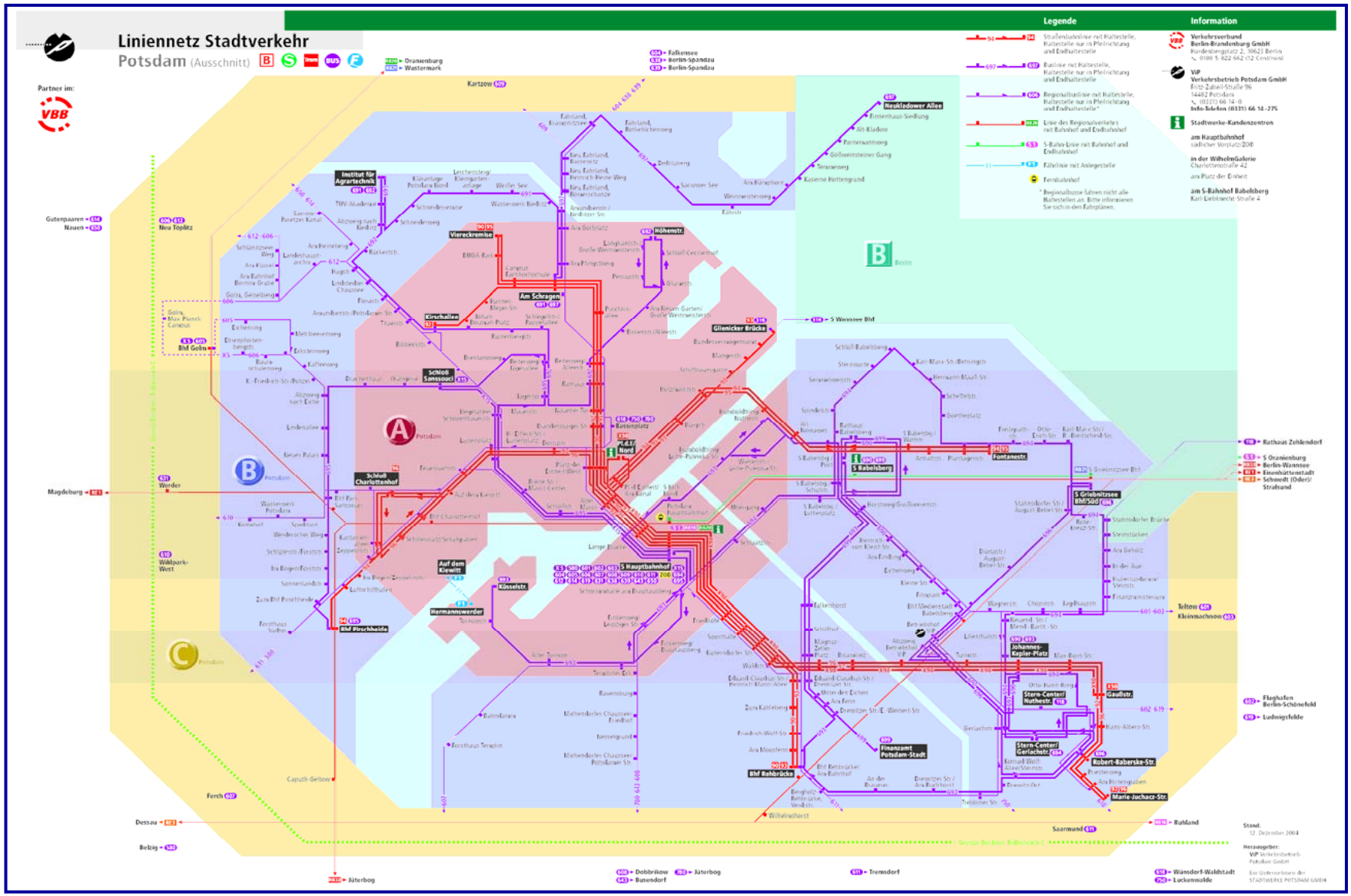
Network, Line and Fare Planning (Potsdam)



Optimization Overview

Optimization of Botany Bay
a Container Terminal in Sydney, Australia

Martin
Grötschel

Gary Froyland, Thorsten Koch, Nicole Megow, Emily Duane, Howard Wren:
Optimizing the Landside Operation of a Container Terminal, OR Spektrum 2007

Port Botany – doubling throughput

Martin
Grötschel

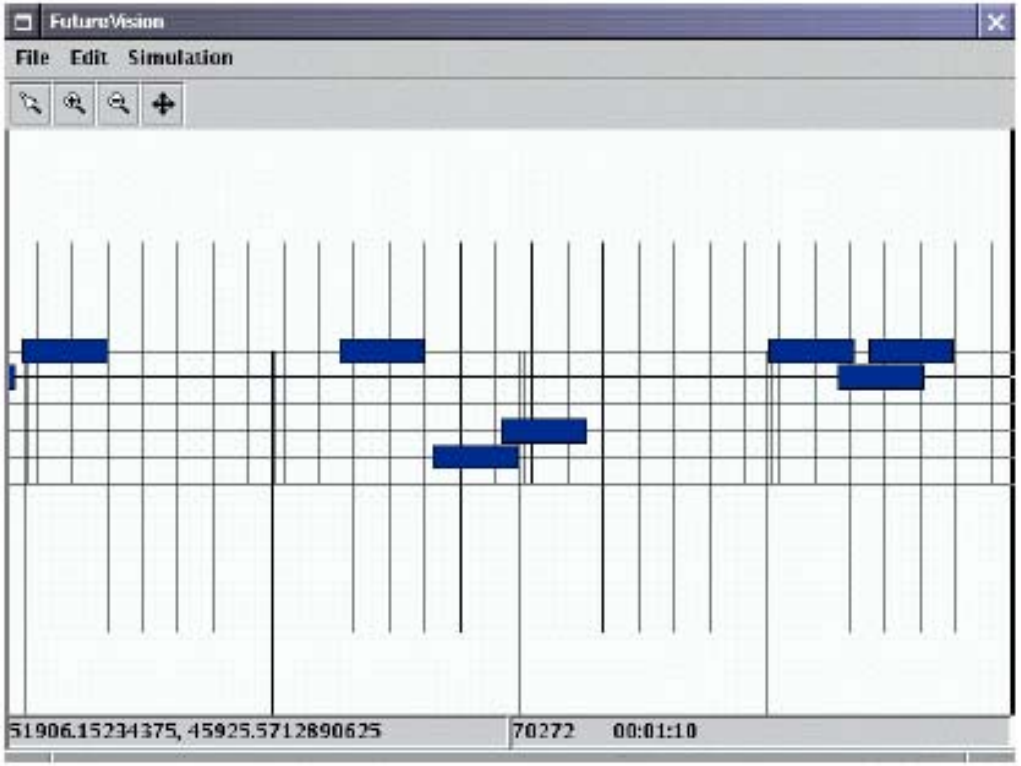
Example: Routing automated guided vehicles in a container terminal in Hamburg Harbor

Cooperation with

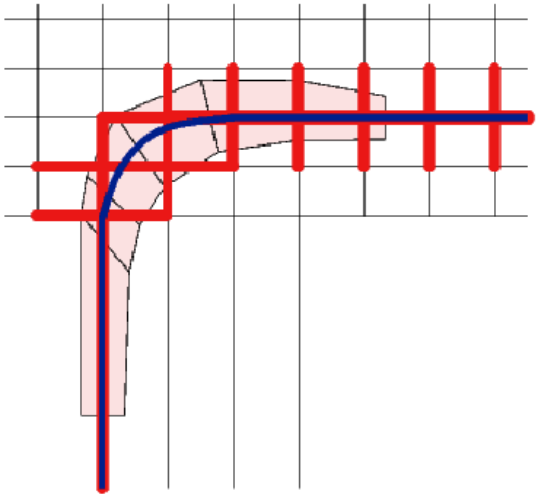
Rolf Möhring's group

Details of AGV routing

Simple grid-like graph



Complex turns of AGVs



„Unit“ of the service fleet:

Yellow Angel

gelber Engel

Supereinsatz. In Berlin und Brandenburg mussten die Gelben Engel letztes Jahr mehr als 240 000 Mal ausrücken, um Havaristen in der Hauptstadt und auf 1700 Autobahnkilometern wieder flottzumachen – ein Rekordeinsatz. Einen Rückgang von zehn Prozent bei den Pannen registrierten dagegen die Gelben Engel in Mecklenburg-Vorpommern. Bei insgesamt 72 389 Einsätzen schafften sie jedoch auch einen Rekord: In 84 Prozent der Fälle konnten die Autofahrer mit dem Wagen weiterfahren.

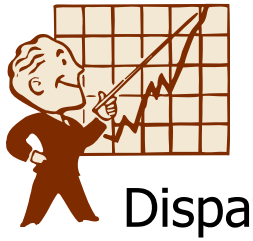
Martin Grötschel

Service vehicle planning at ADAC

Help center

Wireless data transmission

Yellow Angel



Dispatch:
human operator

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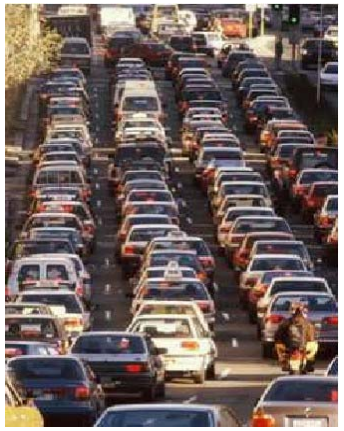
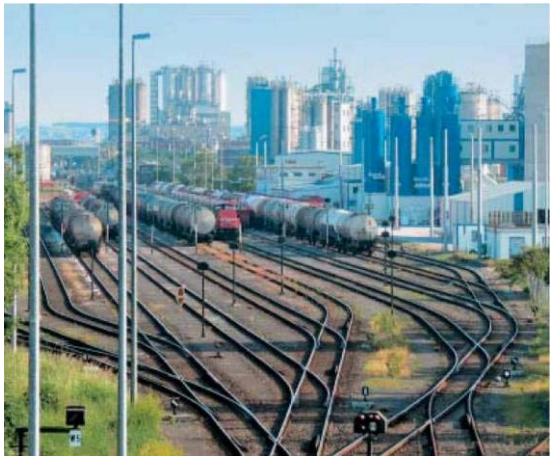
Matheon B8: Flows over Time, a general issue

Routing in a container terminal



Control of traffic lights

Applications



Shunting of trains

Flow of materials in storage areas

Contents

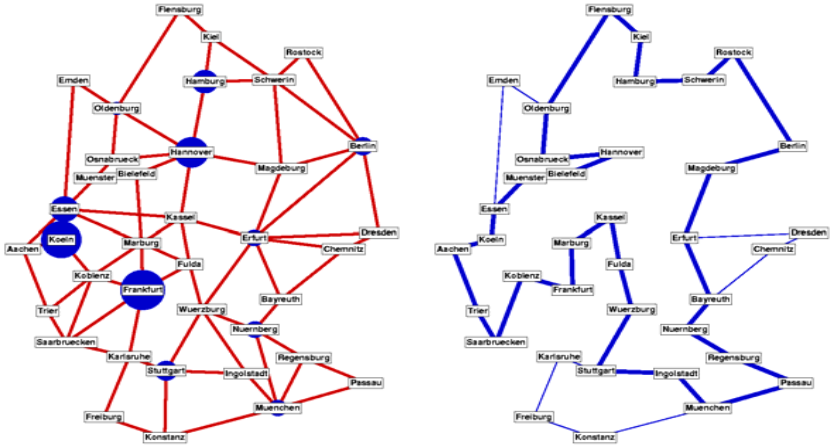
Telecommunication topics: Hardware and logistics

- Designing mobile phones
  - Task partitioning
  - Chip design (VLSI)
  - Component design
- Producing Mobile Phones
  - Production facility layout
  - Control of CNC machines
  - Control of robots
  - Cutting and welding
  - Printed Circuit Boards
    - Via minimization
    - Component Placement
    - Mounting Devices
    - Routing
  - Lot sizing
  - Scheduling
  - Logistics
- Marketing and Distributing Mobile Phones



The Basic Question

Telecommunication network design:



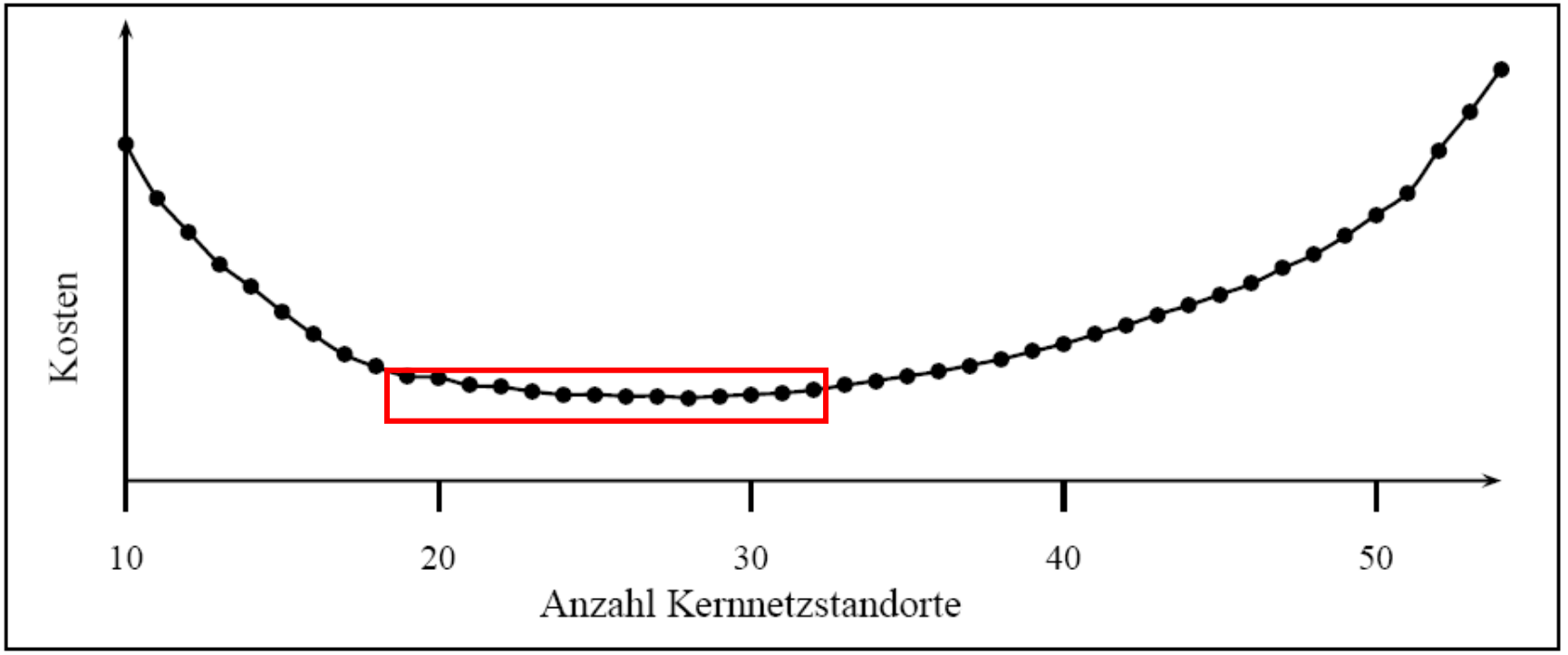
Input:

- potential network
- demands
- cost values
- various additional constraints

Output: cost-minimal

- subset of nodes and links
- discrete capacities
- survivable routing
- satisfying all constraints

Number of Nodes in the Core Network



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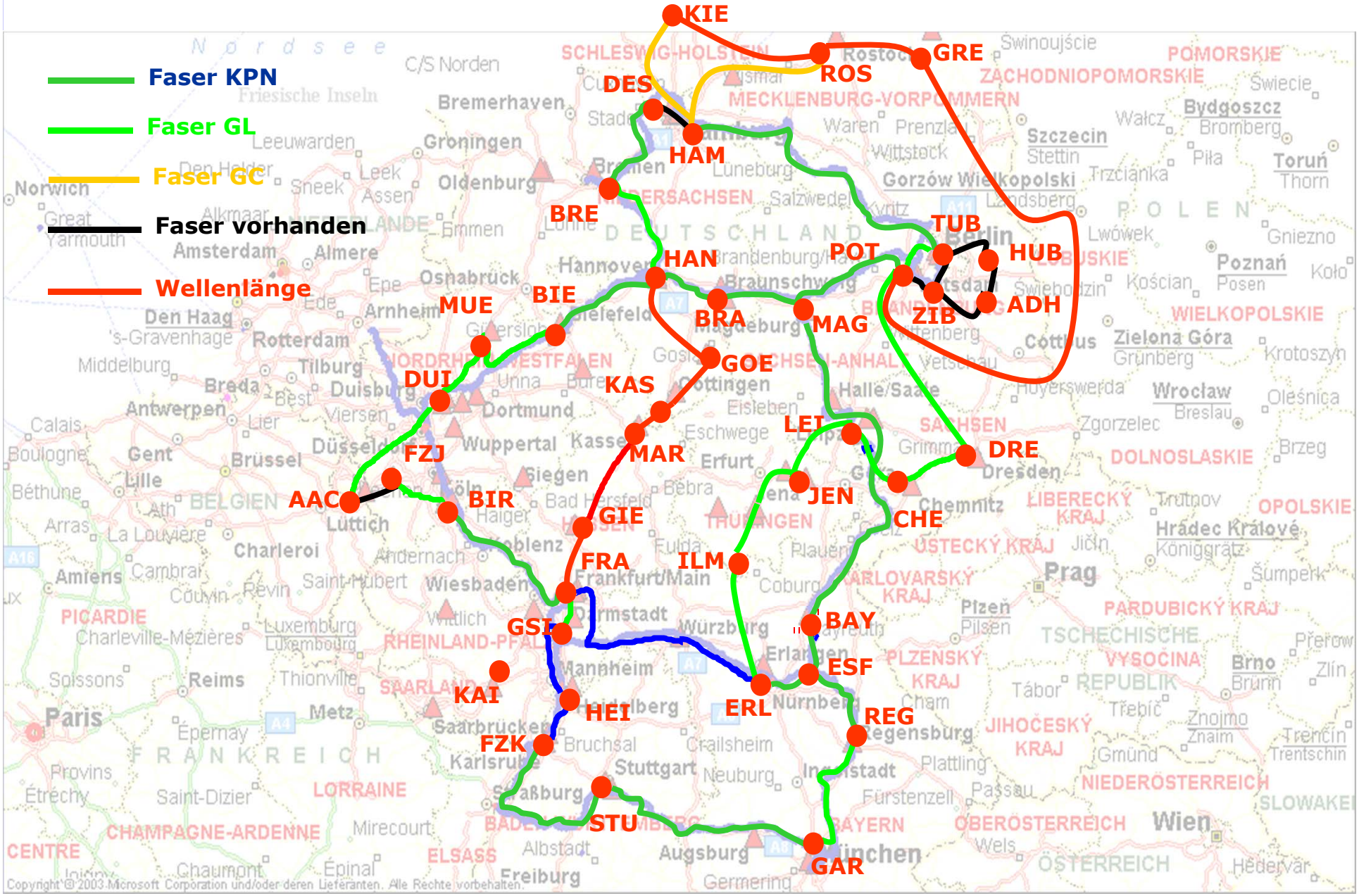
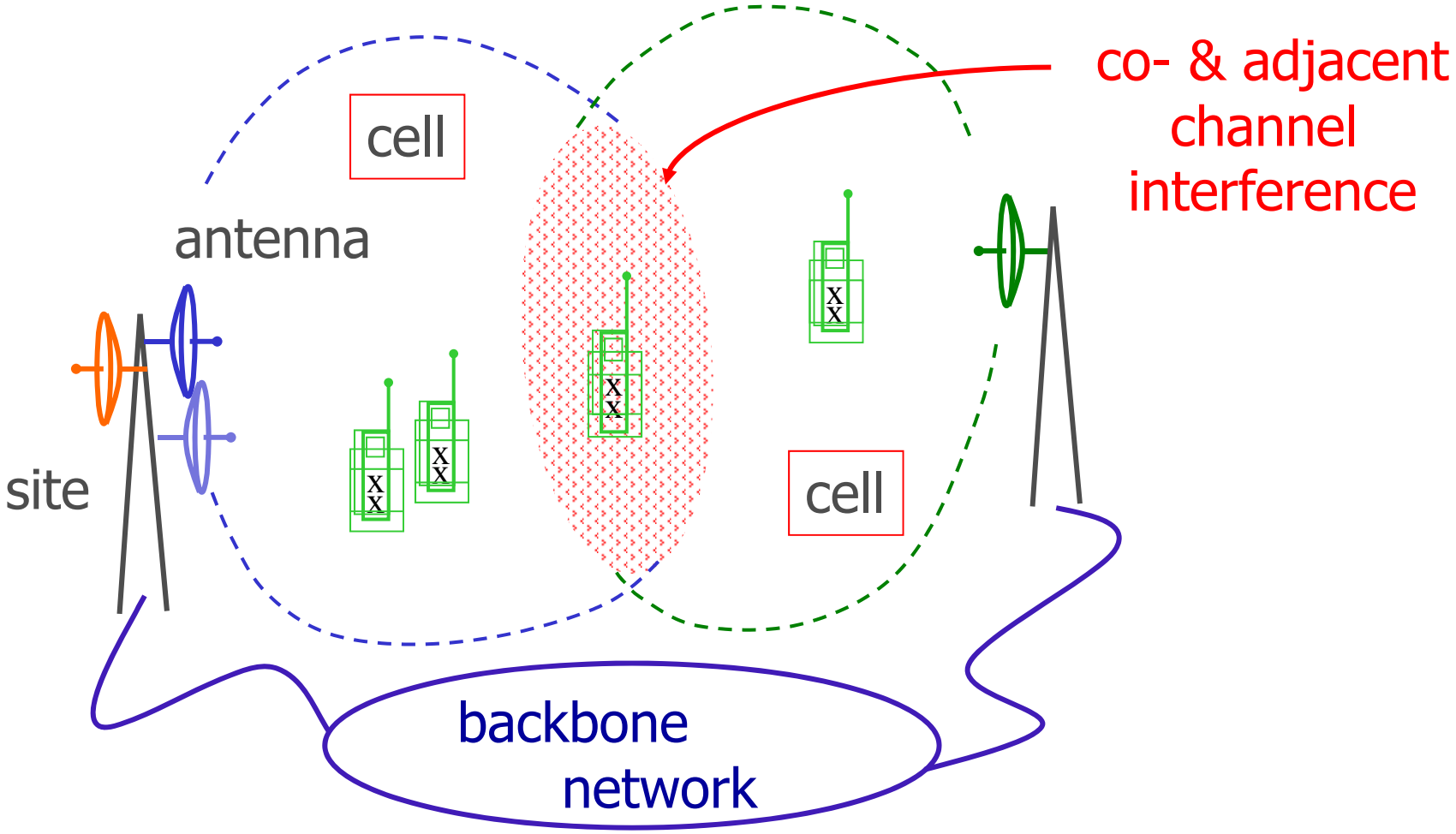
Location- and Network Topology Planing: solvable to optimality in practice



Antennas & Interference



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Minimum Interference Frequency Assignment Problem (FAP)

FAP is an Integer Linear Program:

$$\min \quad \sum_{vw \in E^{co}} c_{vw}^{co} z_{vw}^{co} + \sum_{vw \in E^{ad}} c_{vw}^{ad} z_{vw}^{ad}$$

$$s.t. \quad \sum_{f \in F_v} x_{vf} = 1 \qquad \forall v \in V$$

$$x_{vf} + x_{wg} \le 1 \qquad \forall vw \in E^{d}, |f-g| < d(vw)$$

$$x_{vf} + x_{wf} \le 1 + z_{vw}^{co} \qquad \forall vw \in E^{co}, f \in F_v \cap F_w$$

$$x_{vf} + x_{wg} \le 1 + z_{vw}^{ad} \qquad \forall vw \in E^{ad}, |f-g| = 1$$

$$x_{vf}, z_{vw}^{co}, z_{vw}^{ad} \in \{0,1\}$$

that is very difficult to solve.

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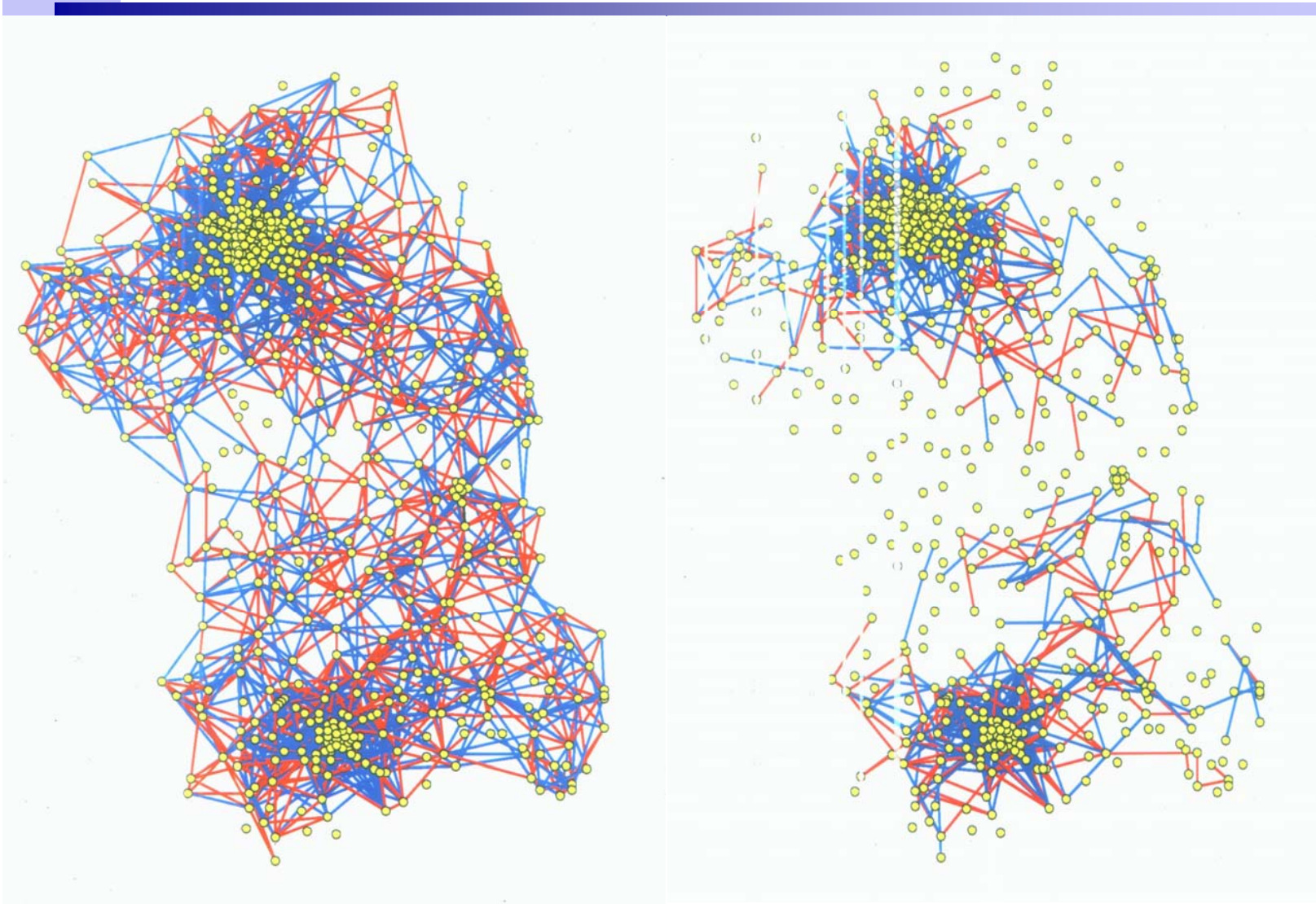
Region Berlin - Dresden

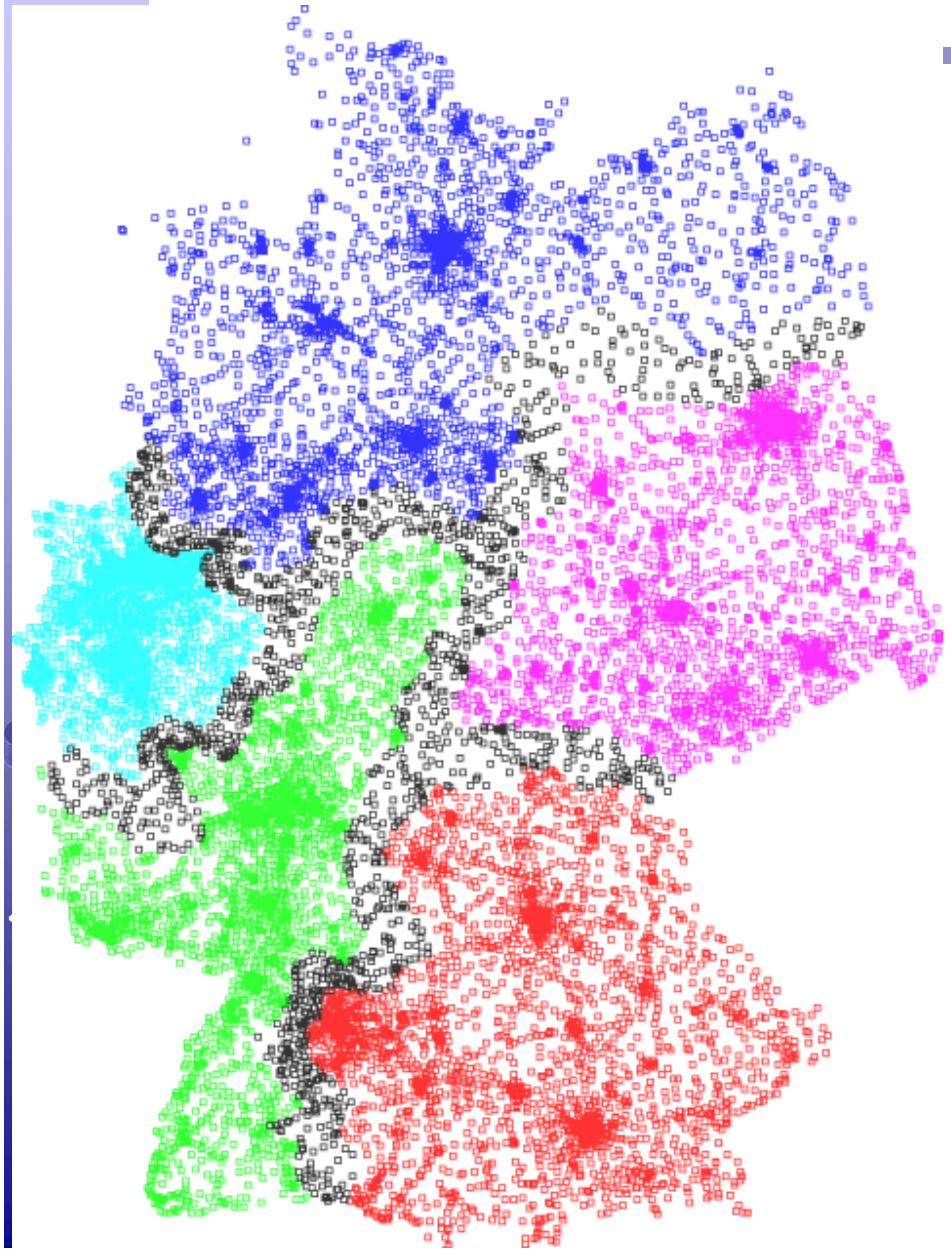


2877 carriers

50 channels

Interference reduction: 83.6%

GSM 900-Optimization in Germany

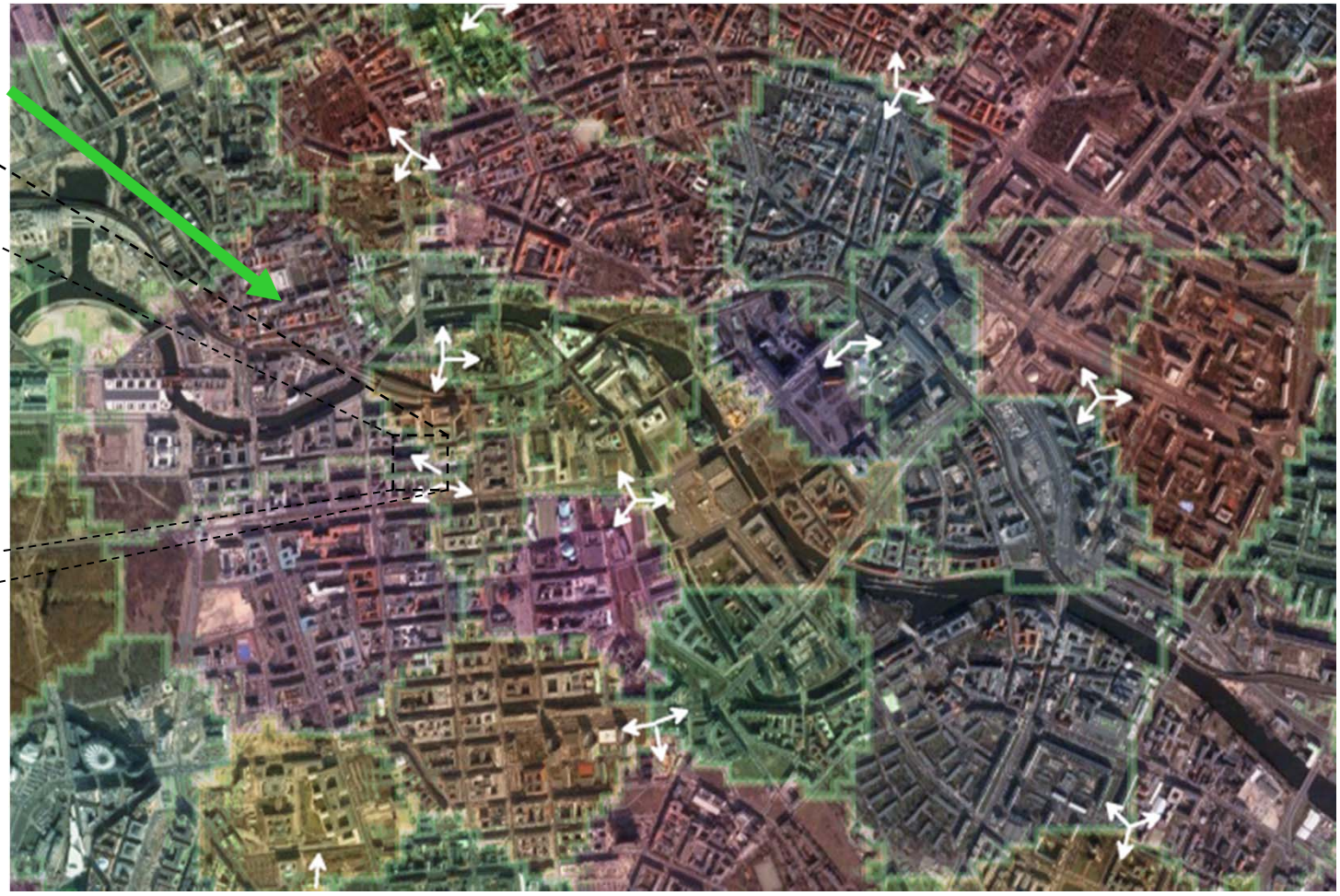


1. Optimierung je Region aller
   - Standorte
   - Sektoren
   - Bänder
2. Zusammenführung der Ergebnisse aller Regionen
3. Optimierung eines Streifens entlang der Regionsgrenzen
4. Optimierung des 1800 MHz-Anteils von Dualband-Sektoren

UMTS-Network

Cell

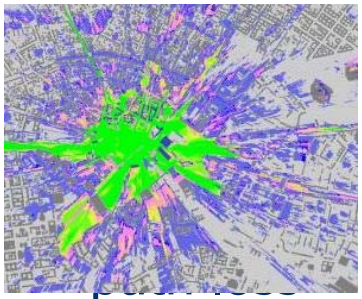
Antenna



Configuration of Antennas

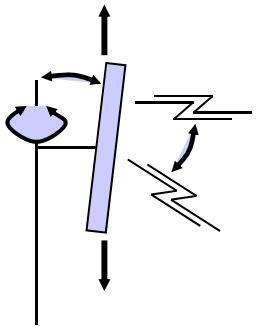
Isotropic Prediction

- Available for each potential antenna location



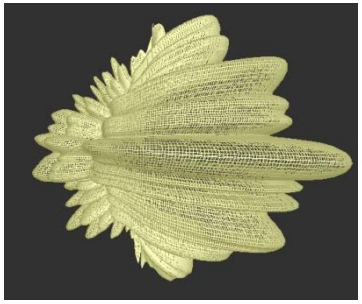
Antenna Configuration

- Azimuth
- Tilt
- Height

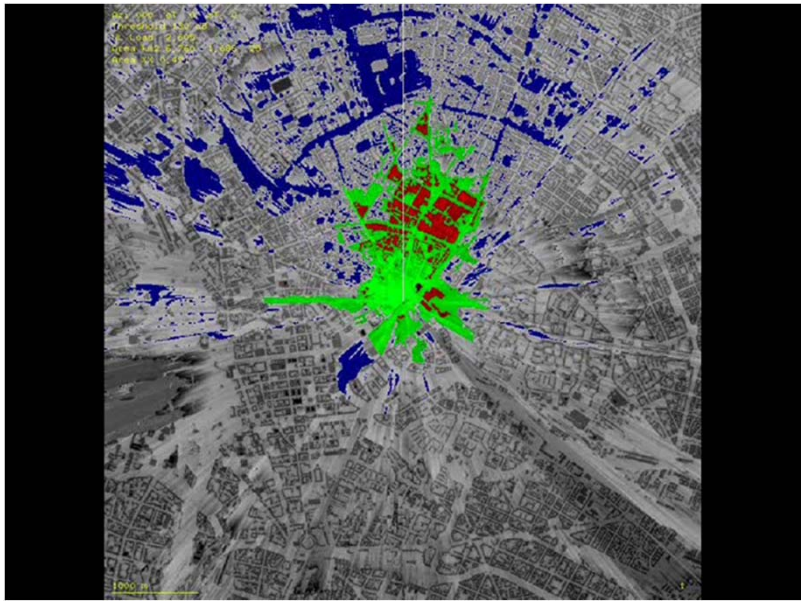


Antenna Diagram

- Signal propagation in different directions



Antenna Prediction

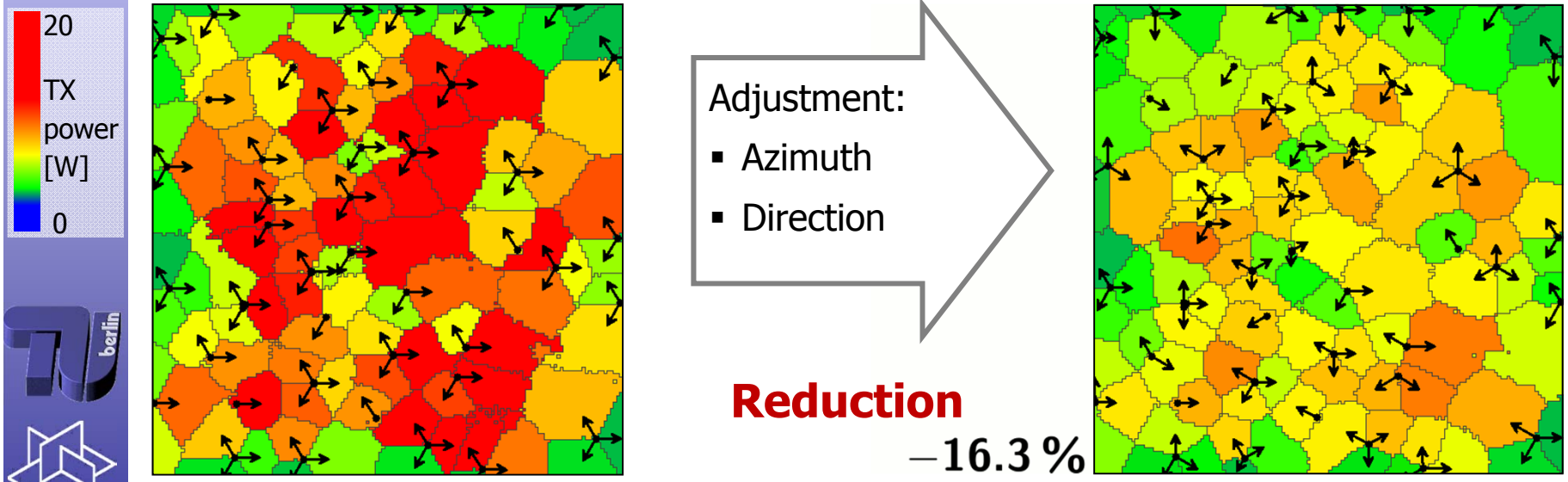


height: 41m, electrical tilt: 0-8°, azimuth 0-120°

Martin Grötschel

Optimization: Reduction of Network Load

Start-Configuration



Adjustment:

- Azimuth
- Direction

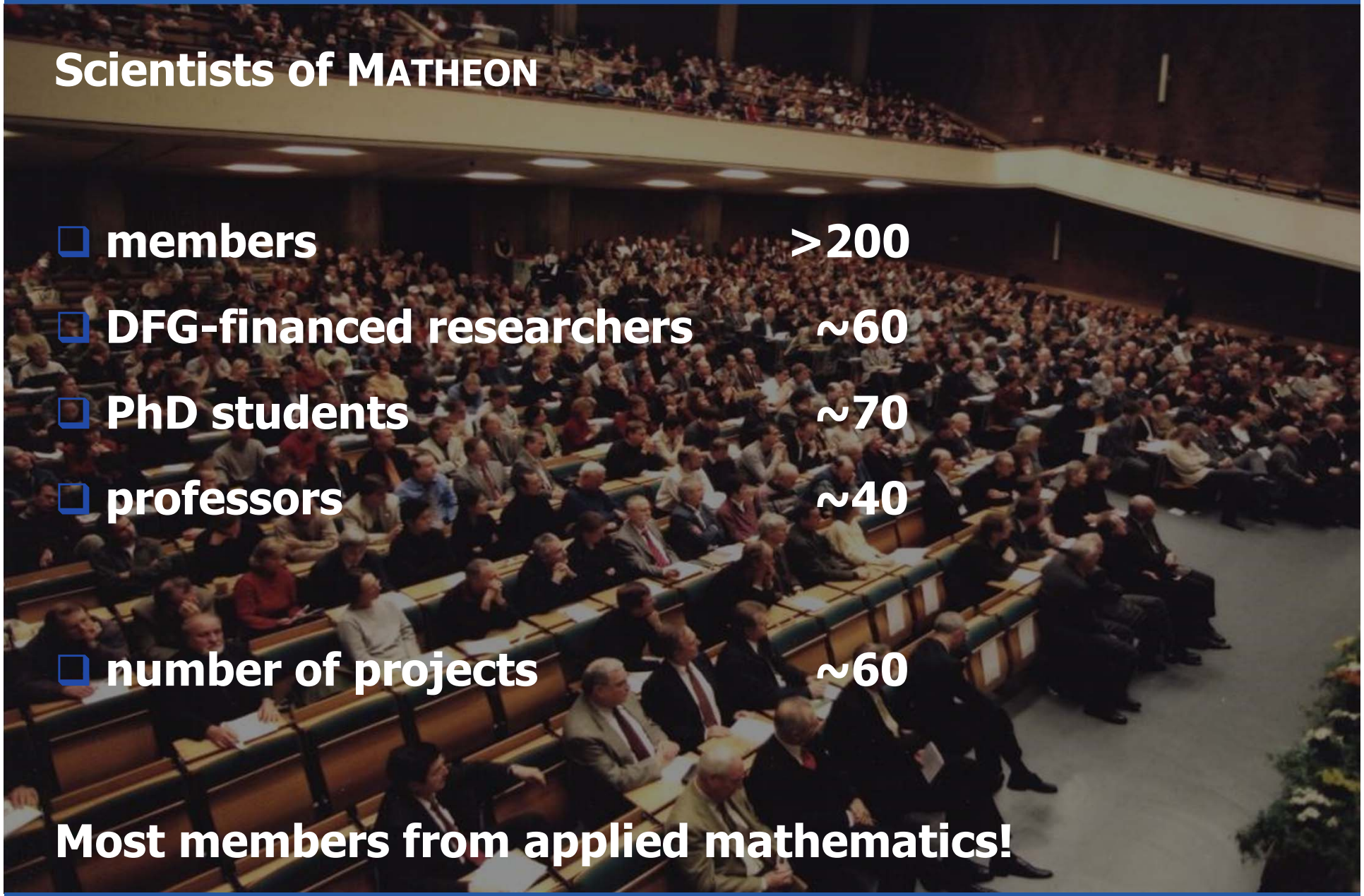
Reduction

−16.3 %

Optimized Configuration

Contents

MATHEON: A Large Competence Pool



Scientists of MATHEON

- members >200
- DFG-financed researchers ~60
- PhD students ~70
- professors ~40

- number of projects ~60

Most members from applied mathematics!

Mathematical Fields and **Application Areas**

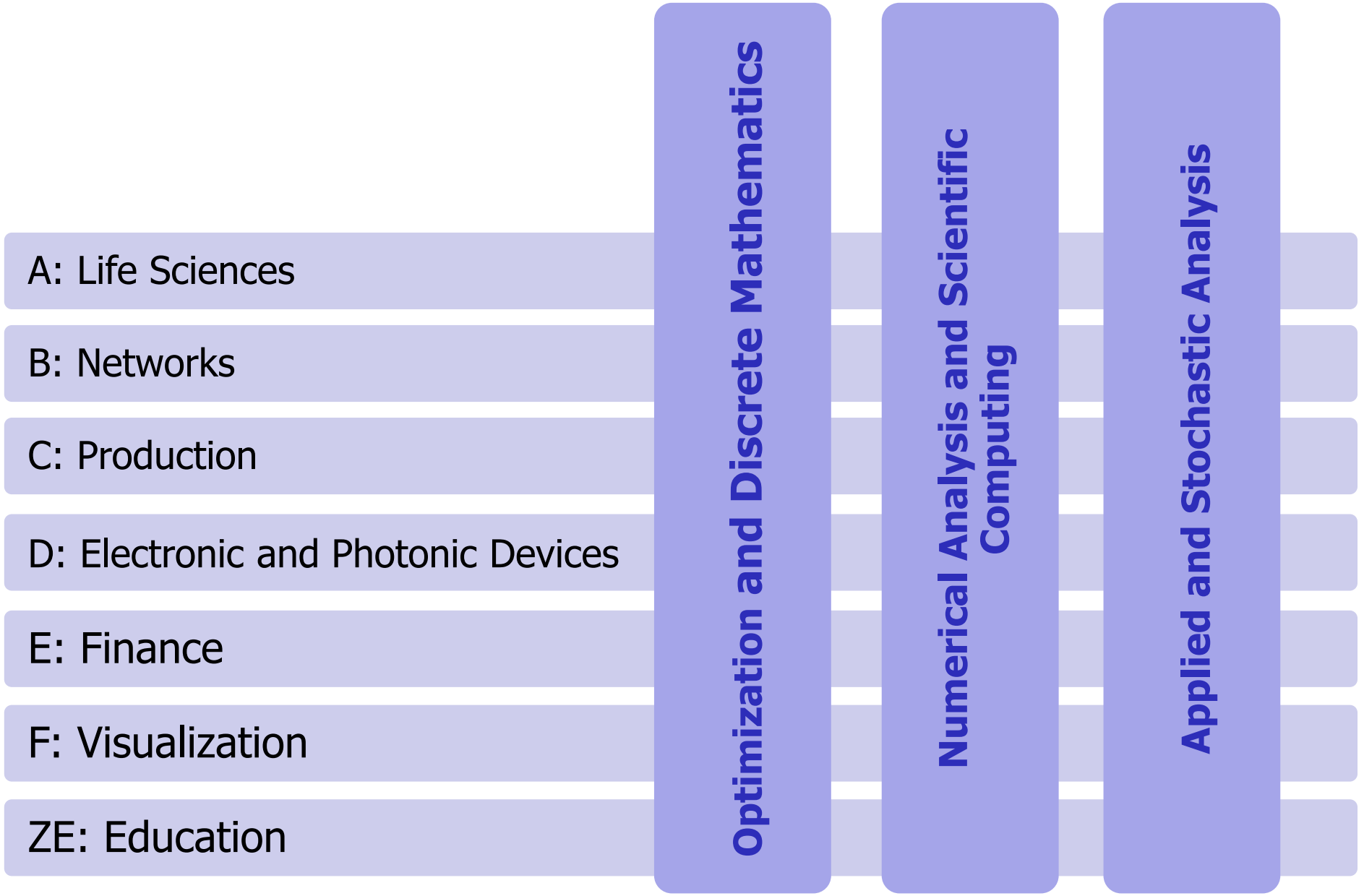
- A: Life Sciences
- B: Networks
- C: Production
- D: Electronic and Photonic Devices
- E: Finance
- F: Visualization
- ZE: Education

Optimization and Discrete Mathematics

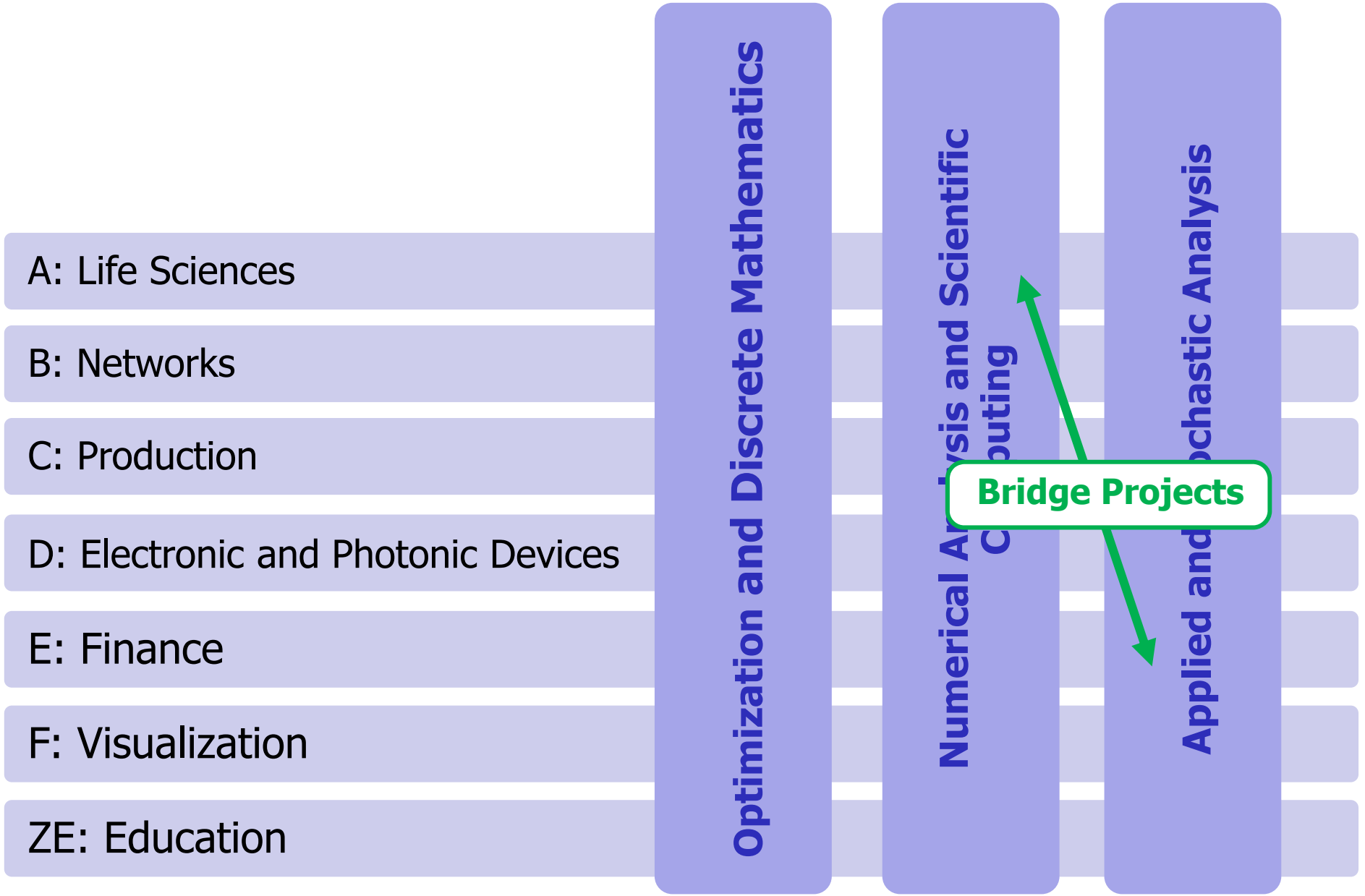
Numerical Analysis and Scientific Computing

Applied and Stochastic Analysis

Added Value through Cooperation across Fields



Added Value through Cooperation across Fields



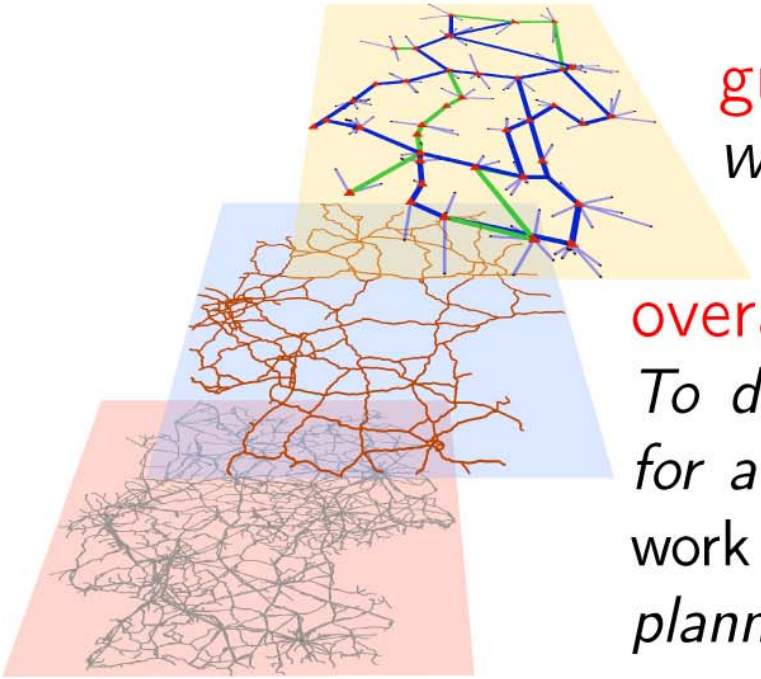
Industry cooperation - examples

- BASF, Bayer-Schering, Merck, Sanofi-Aventis, ...
- Siemens, IBM, Infineon, Microsoft, NEC, SAP, Philips, ...
- Deutsche Telekom (T-Systems), E-Plus, ...
- Daimler, BMW, Volkswagen, Tebis, Bosch, ...
- Deutsche Bahn, BVG, IVU, Lufthansa, ABB, ADAC, Herlitz, ...
- EdF, DREWAG, Vattenfall, E.ON, OGE, BHP Billiton, ...
- AMRO Bank, Bankgesellschaft Berlin, Commerzbank, Deutsche Bank London, IKB, Reuters Financial Software, ...
- Numerous small and medium enterprises (SME)

Spin-Off Companies

- Indeed Visual Concepts (www.amiravis.com):
  3D data visualization (Amira), today: Mercury
- JCMwave (www.jcmwave.com):
  Simulation software for nano-optical components
- atesio (www.atesio.de):
  Plan, configure, and optimize telecommunication networks
- Löbel, Borndörfer & Weider GbR (www.lbw-berlin.de)
  Optimization and consulting for public transport
- Synoptio (www.synoptio.net)
  Mathematical consulting and software
- Lenné 3D (www.lenne3d.de)
  Digital botany and real-time landscapes
- inbion GmbH (inbion.math.fu-berlin.de)
  Bioinformatics solutions for life sciences

Networks: Our Vision



guiding question:
what constitutes a good network?

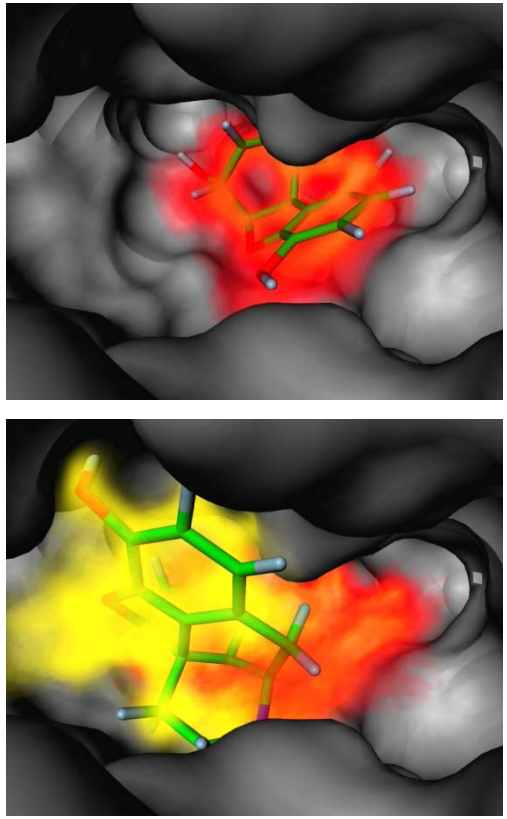
overall goal:
To develop theory, algorithms, and software for a new, advanced level of integrated network optimization *that addresses network planning problems as a whole.*

examples:

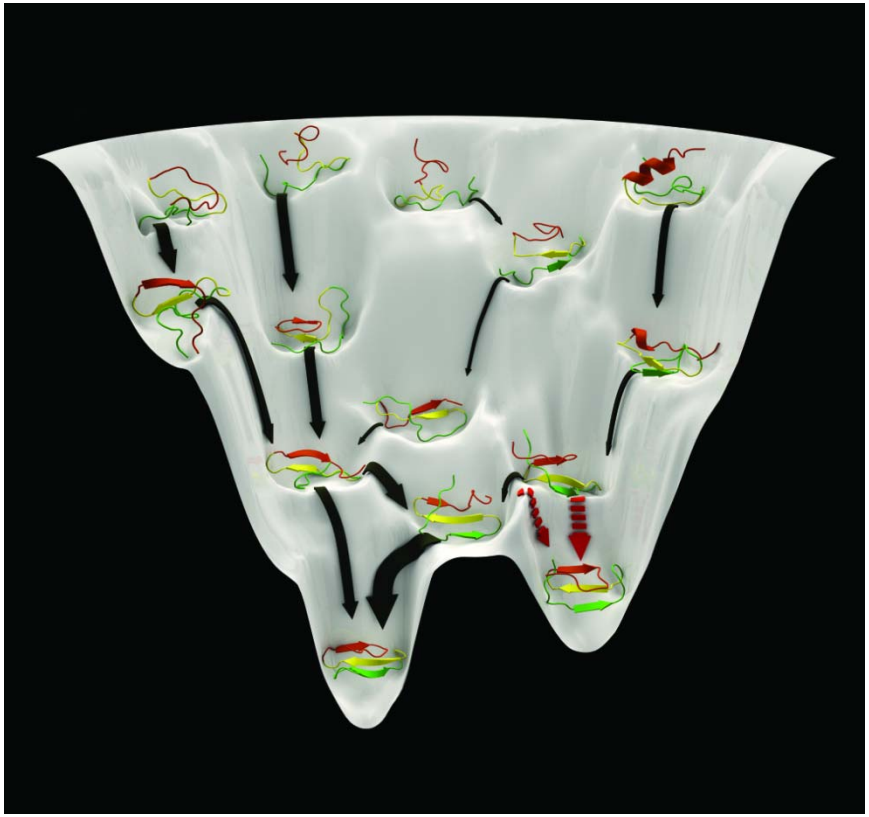
- line planning and timetabling in public transport
- fiber and UMTS telecommunication network design
- harbor and factory logistics

A19 Molecular Design

Drug Design



Protein folding



new pain relief drug

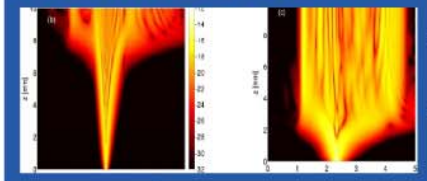
conformation dynamics, meshless methods, transition path theory

Domains of Expertise in MATHEON AA D

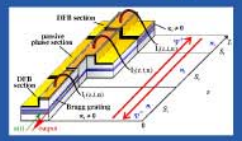
Photonic Devices

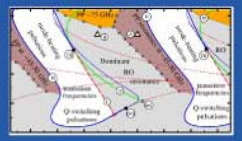
Electronic Devices

D14 Bandelow Mielke:
Nonlinear fibers



D8 Recke Wolfrum:
Laser dynamics





D21 Yanchuk:
Synchronization

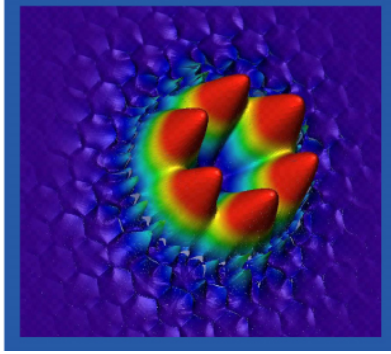
Light

Electric
cu

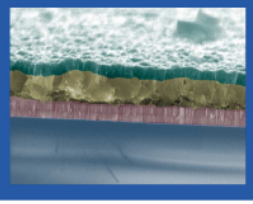
D2 Mehrmann Reis:
Passivation and model reduction

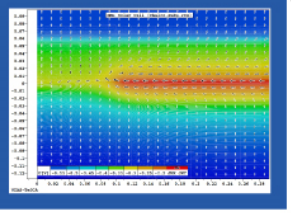
⇝ *next talk*

D23 Schmidt:
Nanostructures



D22 Glitzky Mielke:
Interfaces in solar cells





Record Tandem-Cell with 14% Efficiency

Goal ZIB

Simulation and optimization of solar cell design

Challenge

- 3D simulation of large structures (>5 million unknowns)
- large parameter space

  (materials, thicknesses, roughness, textures)

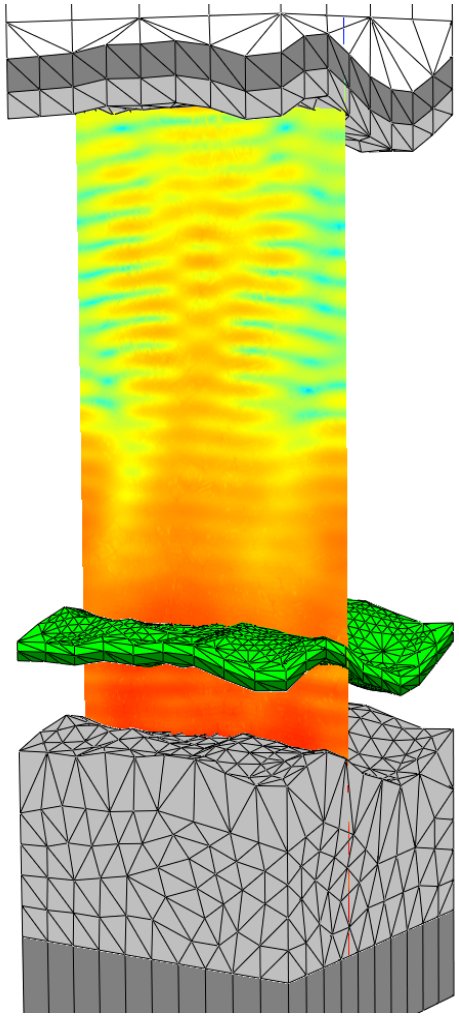
Strategies

- hp-adaptivity
- domain decomposition
- adaptive spectral sampling
- reduced basis algorithms

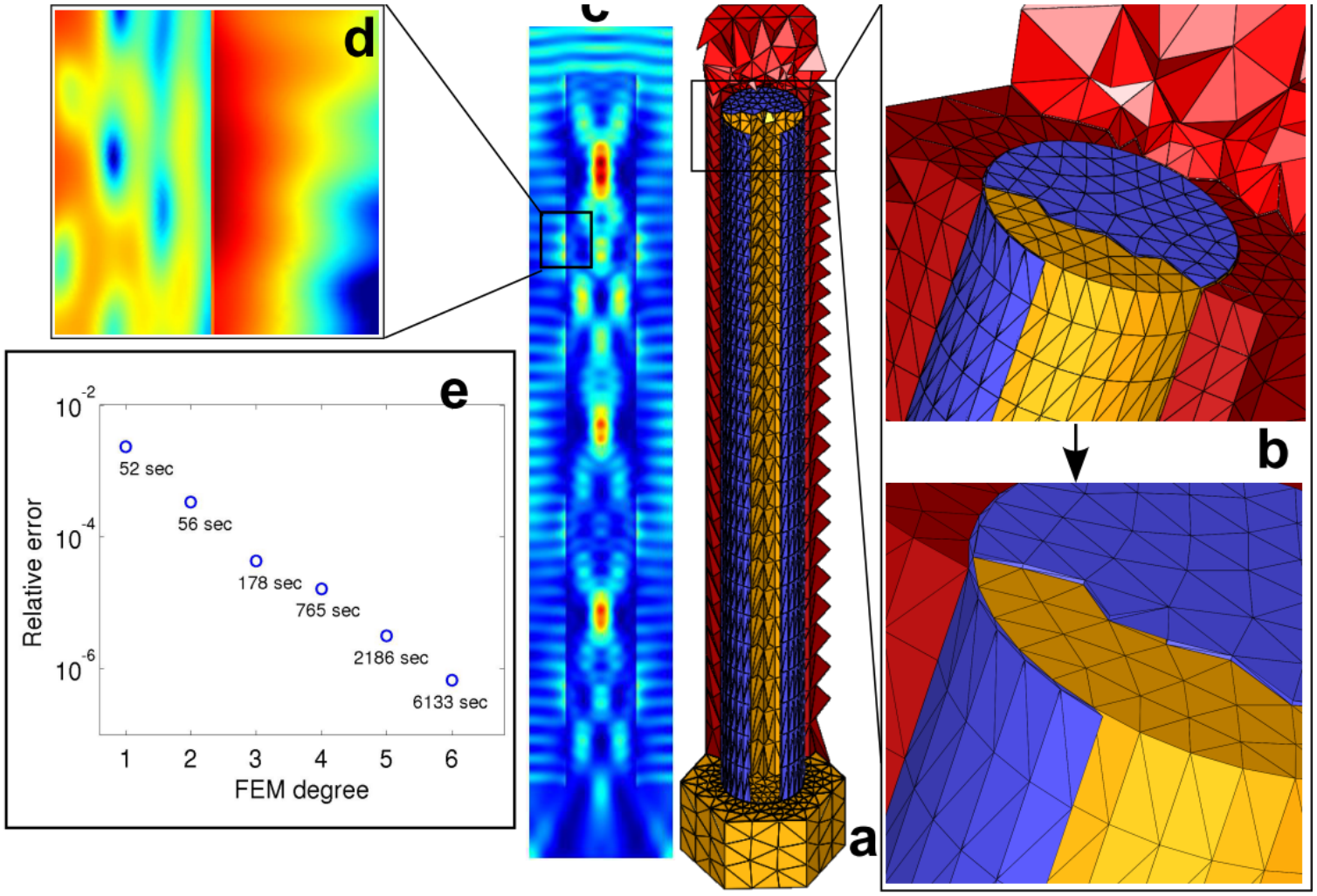
Partners

MASDAR PV
A MASDAR COMPANY

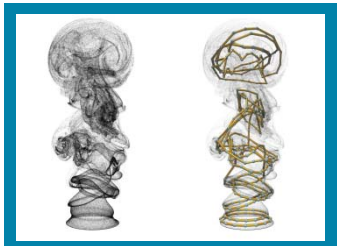
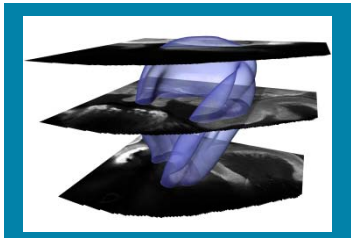
pvcomB



Numerical Study of Nanowires



Visualization: Projects and Domains of Expertise

	Geometry Processing F1 – F4 – F9	Image Processing F2 – F10	Interactive Graphics F5 – F6
Industrial CAD	 F1 Discrete Surface Parametrizations Bobenko/Ziegler	 F4 Geometric Shape Optimization Polthier	 F6 Multilevel Methods Kornhuber/ Polthier/Yserentant
Computer Graphics			  F5 Physics for Interactive Graphics Pinkall/Sullivan
Medicine & Physics	 F9 (C25) Trajectory Compression Polthier/Weiser	 F2 Atlas-based Image Segmentation Hege/Weiser	 F10 (A3) Image and Signal Processing in Medicine & Biosciences Polzehl/Spokoiny

And so on...

Contents



Martin Grötschel

Have you encountered mathematics within the last days? Have I?

I am discussing only mathematics produced in my group:

- mobile phone channel assignment
- e-mail: (communication network and data packages)
- bus circulation in Berlin
- bus driver assignment in Berlin
- subway timetable in Berlin
- Lufthansa plane tail assignment of my flight
- car navigation system
- medical imaging



What to do to be successful in practice: Advice

- Learn (get acquainted with) many branches of mathematics, you never know what you are going to need.
- Make colleagues who know other types of maths better than you your friends. You may need them.
- Don’t be arrogant! Other people are also intelligent, and they may know some things much better than you.
- Learn the language of your customers. They will not have the time and patience to learn your mathematics. But you have to communicate with them. And it is better for everyone that mathematicians learn the “other stuff”.

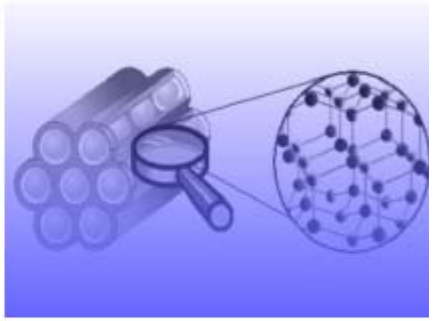


New „Paradigm“: Understanding & utilizing big and complex data sets

Verkehr und Logistik

Hausautomatisierung

Lebenswissenschaften



Materialforschung

Marktforschung

Digital Humanities

Ressourcenmanagement
(„smarter cities/planet“)

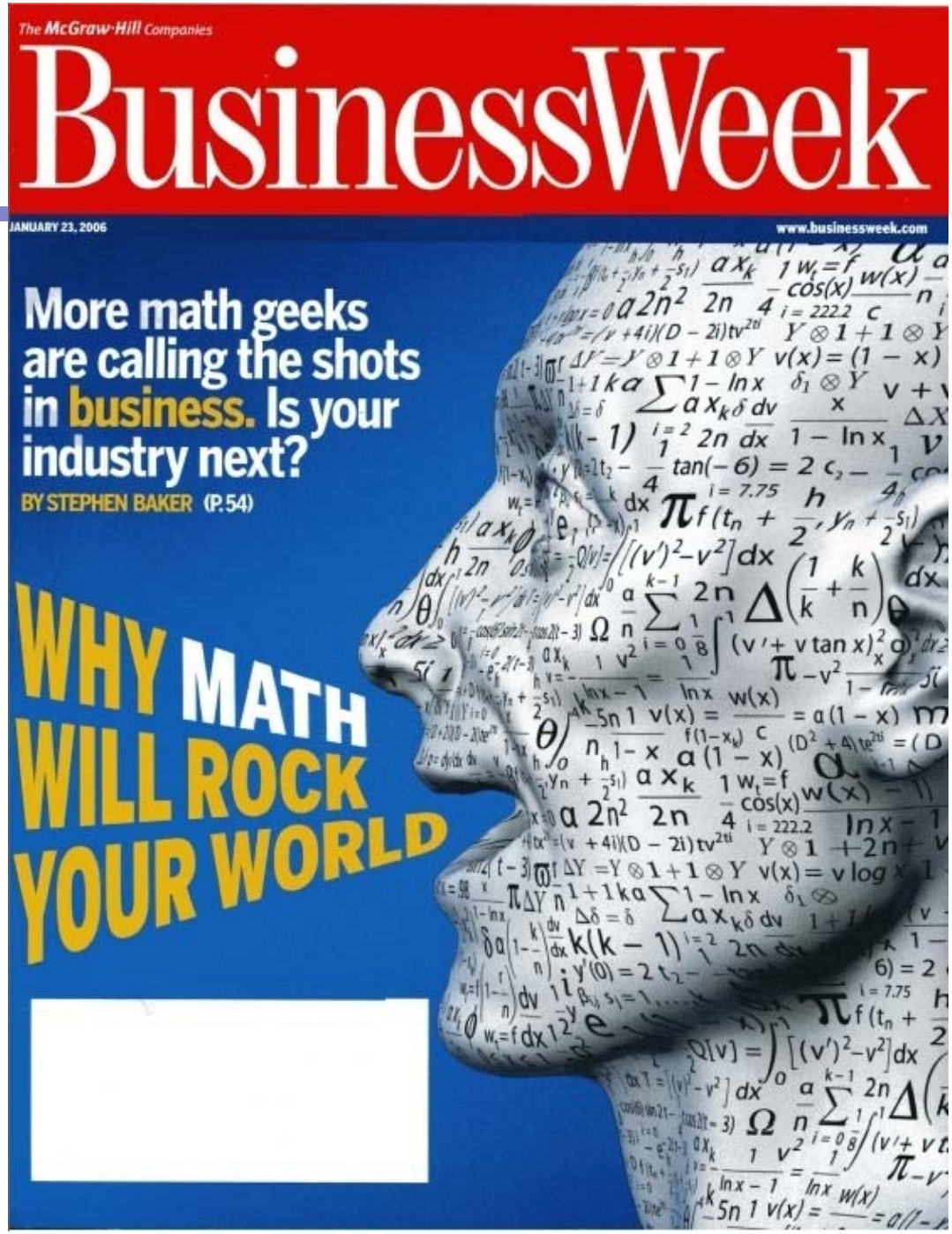
Unternehmenssteuerung

ZIB
Martin Grötschel

From the IBM homepage: "Every day, we create 2.5 quintillion bytes of data — so much that 90% of the data in the world today has been created in the last two years alone."

Business Week of January 23, 2006

For me, mathematics is going to become the most imporant scientific endeavour of the 21st century, because every other science and every technology needs more and more maths. Our industry will not remain competitive without significant utilization of mathematics



Suppose you would eliminate (modern) mathematics from technology

- Would the motor of a modern car run efficiently?
- Would an airplane like A380 fly?
- Would your car navigation system operate?
- Would medical imaging systems (X-ray, MRT, …) show a tumor in the right spot?
- Would public transport be affordable?
- Would your smartphone work?
- Would high communication networks exist?
- Would data transfer be secure?

Mathematics does not provide the services and technologies, but is an essential part of them.

Martin Grötschel

Grand challanges as identified by the US National Academies

THE CHALLENGES

- Make solar energy affordable
- Provide energy from fusion
- Develop carbon sequestration methods
- Manage the nitrogen cycle
- Provide access to clean water
- Restore and improve urban infrastructure
- Advance health informatics
- Engineer better medicines
- Reverse-engineer the brain
- Prevent nuclear terror
- Secure cyberspace
- Enhance virtual reality
- Advance personalized learning
- Engineer the tools for scientific discovery

Personal health

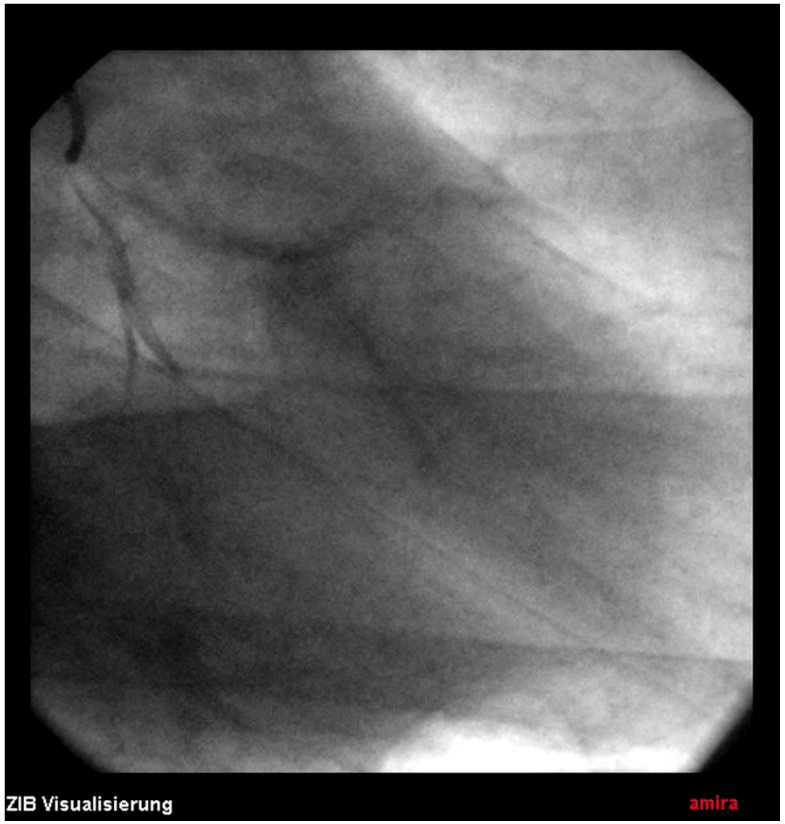
- Diseases are going to hit me and some of you in the audiences in the future or have already done so in the past – though I hope they will not.
- Two examples



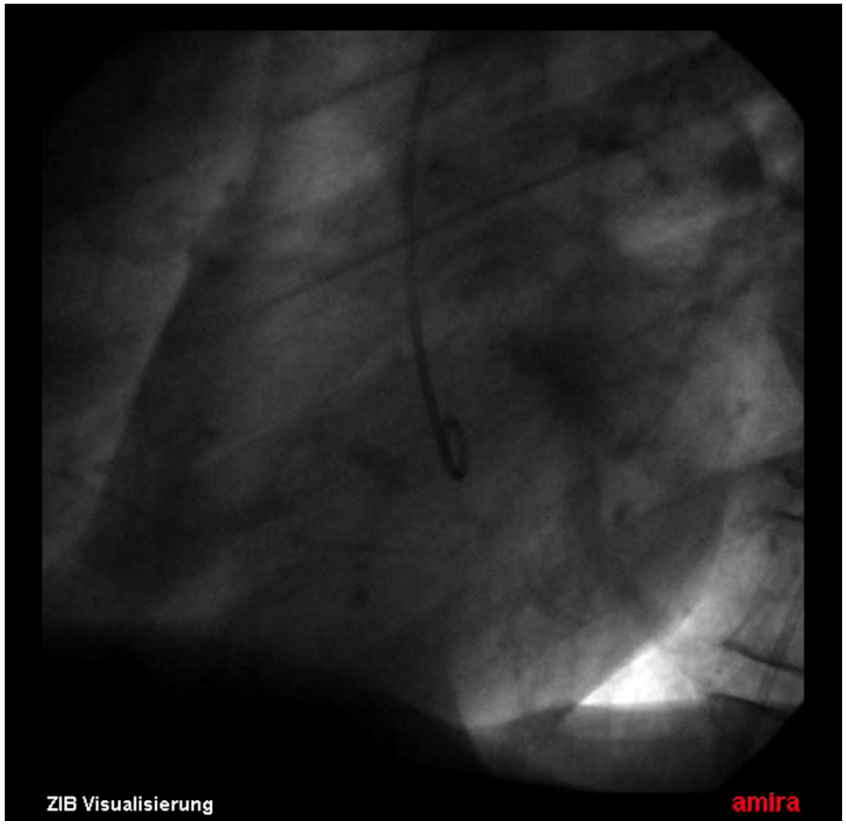
Martin Grötschel

My Heart

Vorhof-Flattern
atrial fibrilation



Ablation



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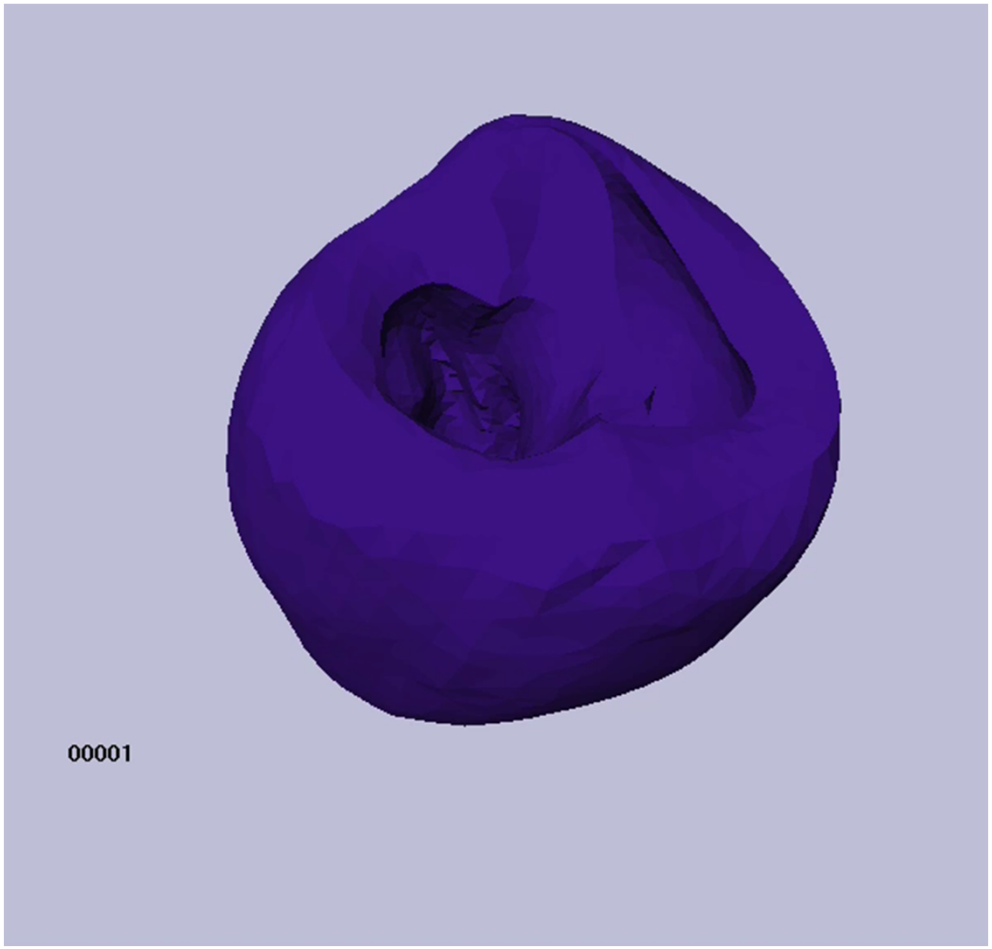
Cardio Fibrillation



Peter Deuflhard's group at ZIB

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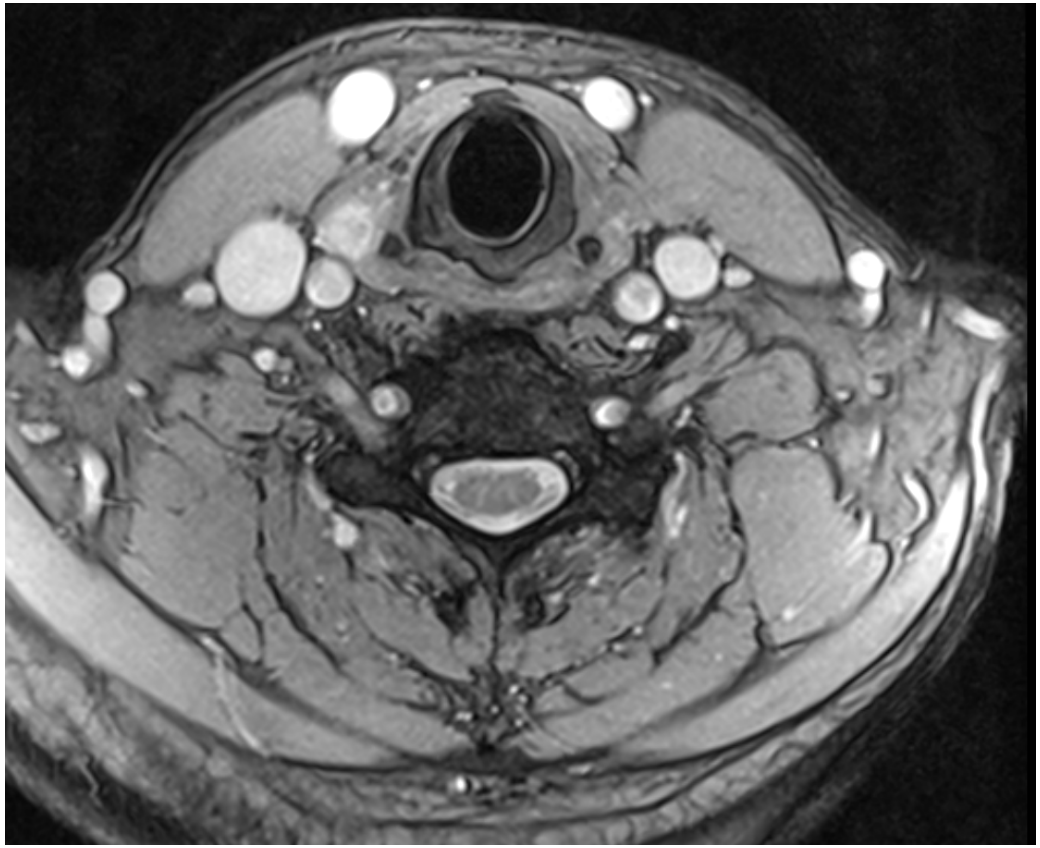
Grötschel

Magnetic Resonance Tomography (MRT)

My own spine 28.08.2013
operation on 03.09.2013



Overview on Applications: Is (advanced) mathematics useful? CO@W Berlin

Thanks for your attention

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- Forschungszentrum MATHEON
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