Advanced Route Planning

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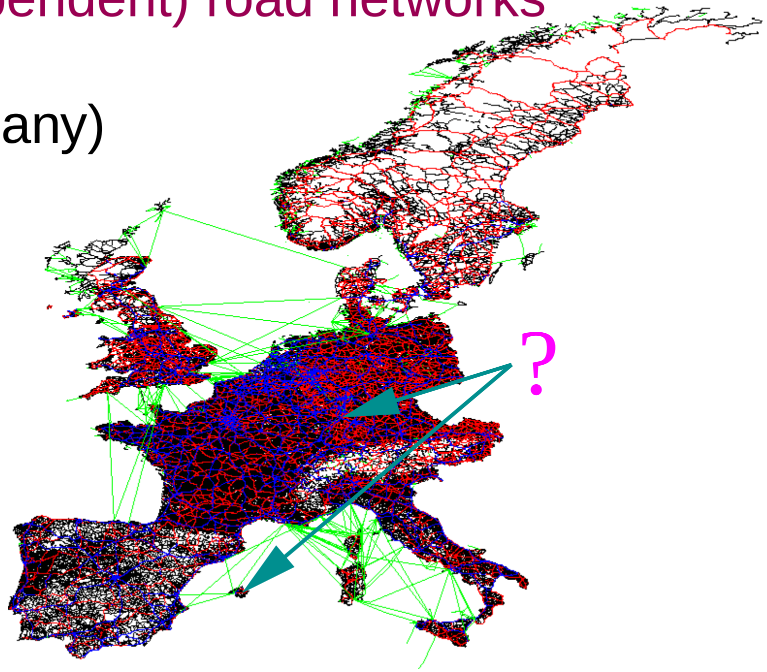
University + Research Center ≈ largest research inst. in Germany

Route Planning

Goals:

- exact shortest paths in large (time-dependent) road networks
- fast queries (point-to-point, many-to-many)
- fast preprocessing
- low space consumption
- fast update operations



Applications:

- route planning systems in the internet, car navigation systems,
- ride sharing, traffic simulation, logistics optimisation

Advanced Route Planning

What we can do:

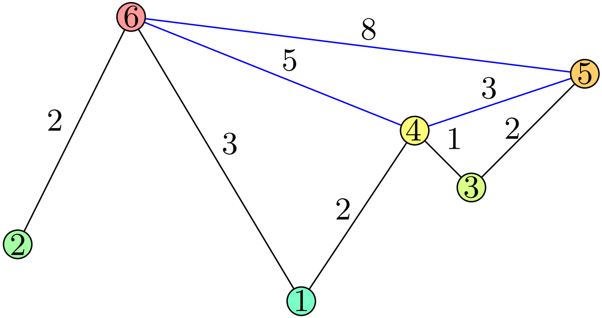
- ☐ plain static routing (very fast)
- ☐ distance tables (even faster)
- ☐ turn penalties
- ☐ mobile implementation
- ☐ time dependent edge weights
- ☐ flexible objective functions
- ☐ traffic jams

Advanced Route Planning

What we are working on:

- energy efficient routes
- modelling alternative routes
- detouring traffic jams realistically
- integration with public transportation
- novel applications

Contraction Hierarchies (CH)



Main Idea

Contraction Hierarchies (CH)

- contract only one node at a time
  $\Rightarrow$ local and cache-efficient operation

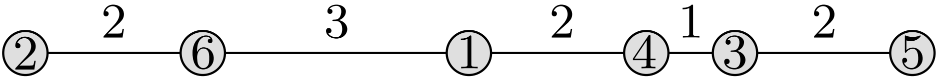
in more detail:

- order nodes by “importance”, $V = \{1, 2, \ldots, n\}$
- contract nodes in this order, node v is contracted by

  foreach *pair* (u, v) *and* (v, w) *of edges* **do**
      if $\langle u, v, w \rangle$ *is a unique shortest path* **then**
          add shortcut (u, w) with weight $w(\langle u, v, w \rangle)$

- query relaxes only edges to more “important” nodes
  $\Rightarrow$ valid due to shortcuts

Example: Construction



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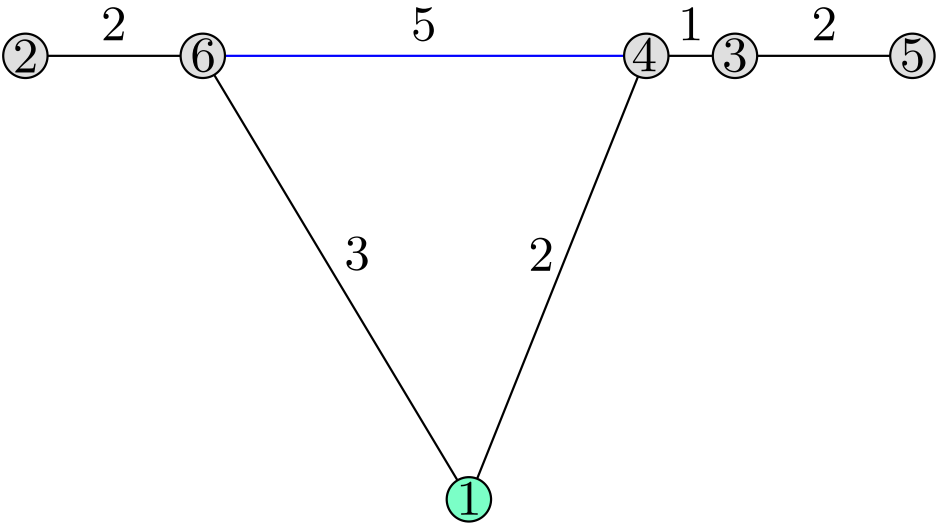

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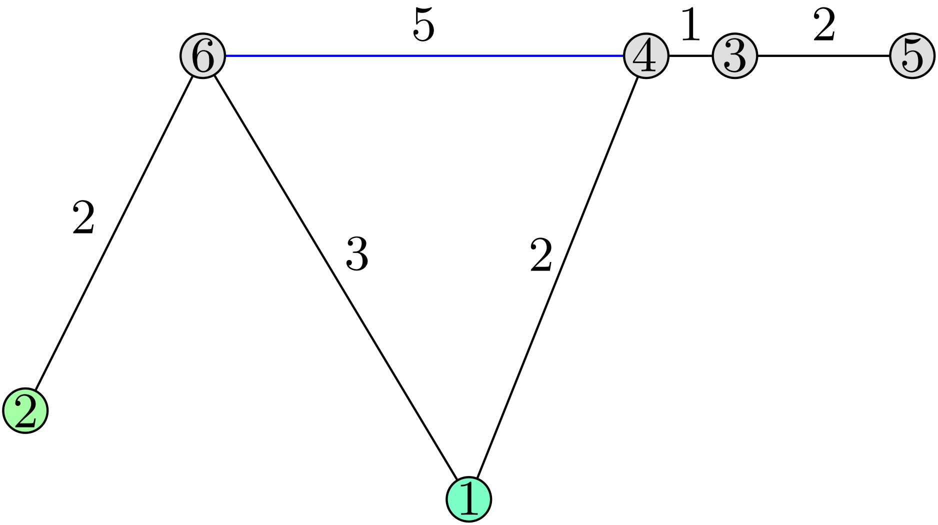

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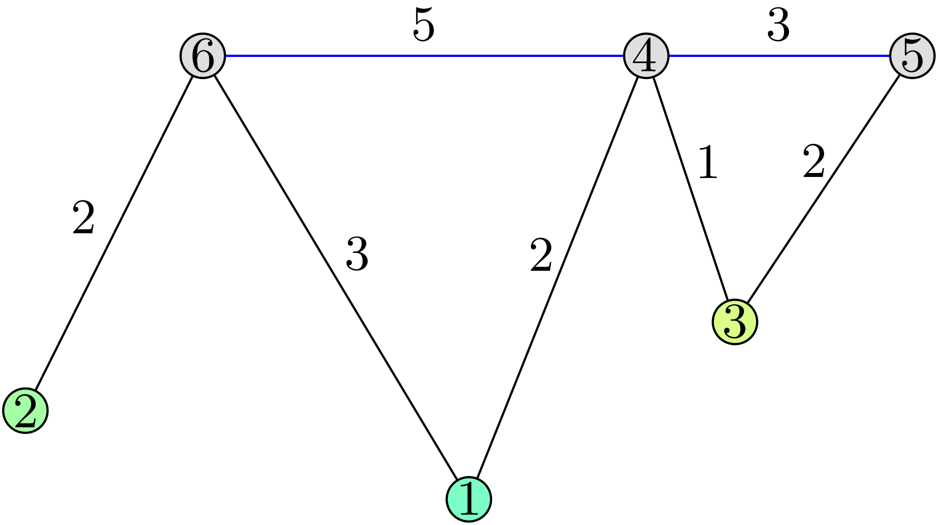

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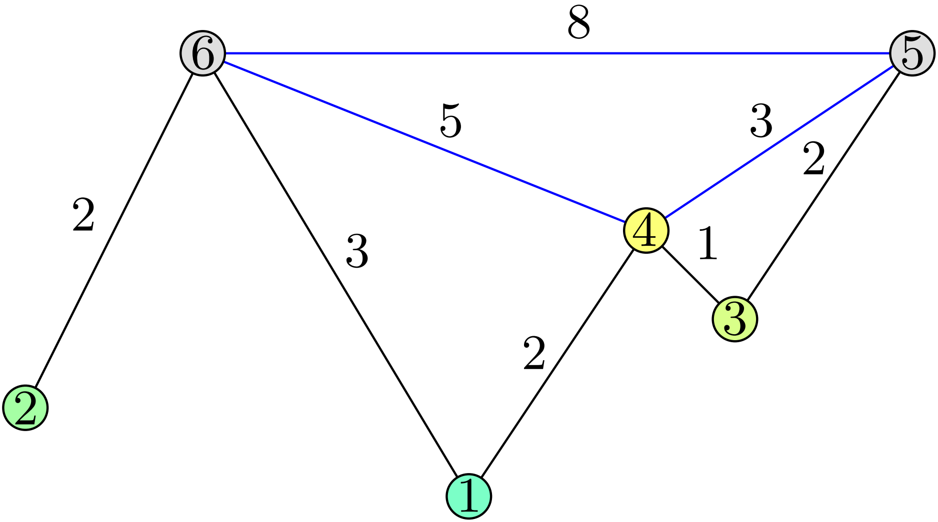

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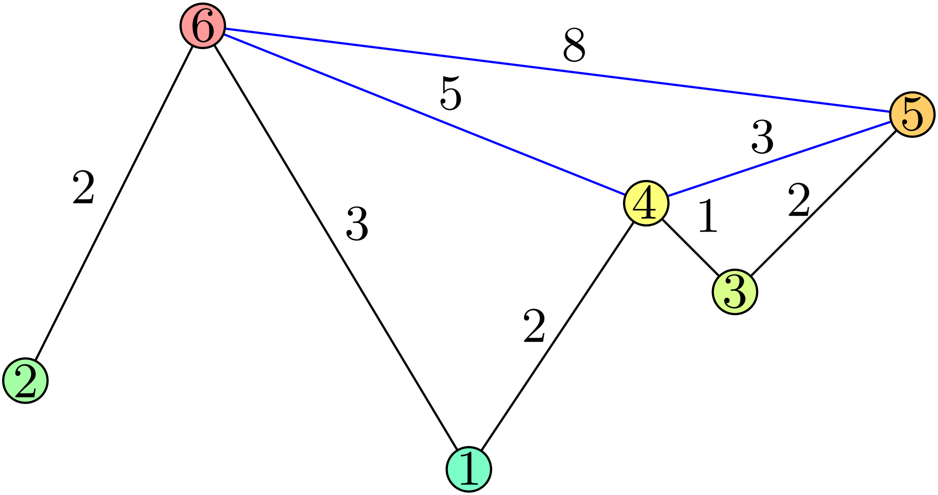
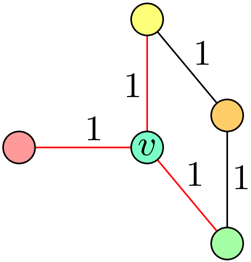


Construction

to identify necessary shortcuts

- local searches from all nodes u with incoming edge (u, v)
- ignore node v at search
- add shortcut (u, w) iff found distance $d(u, w) > w(u, v) + w(v, w)$



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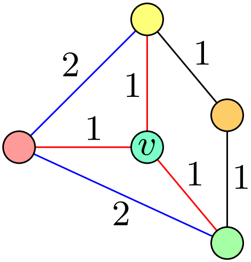
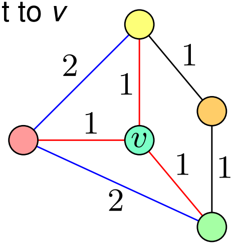


Node Order

use priority queue of nodes, node v is weighted with a linear combination of:

- **edge difference** #shortcuts – #edges incident to v
- **uniformity** e.g. #deleted neighbors
- ...



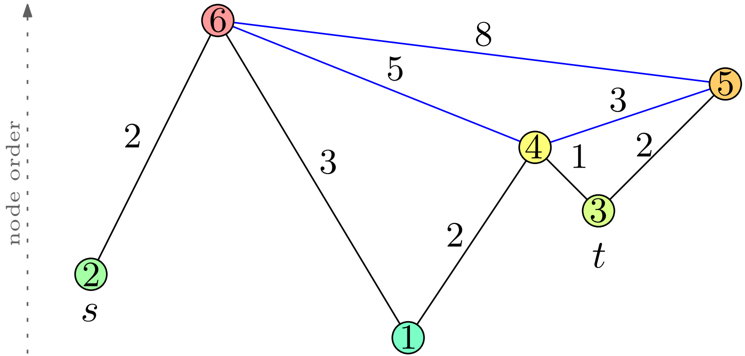
$2 - 3 = -1$

integrated construction and ordering:

1. remove node v on top of the priority queue
2. contract node v
3. update weights of remaining nodes

Query

- modified bidirectional Dijkstra algorithm
- upward graph $G_\uparrow := (V, E_\uparrow)$ with $E_\uparrow := \{(u, v) \in E : u < v\}$
  downward graph $G_\downarrow := (V, E_\downarrow)$ with $E_\downarrow := \{(u, v) \in E : u > v\}$
- forward search in $G_\uparrow$ and backward search in $G_\downarrow$



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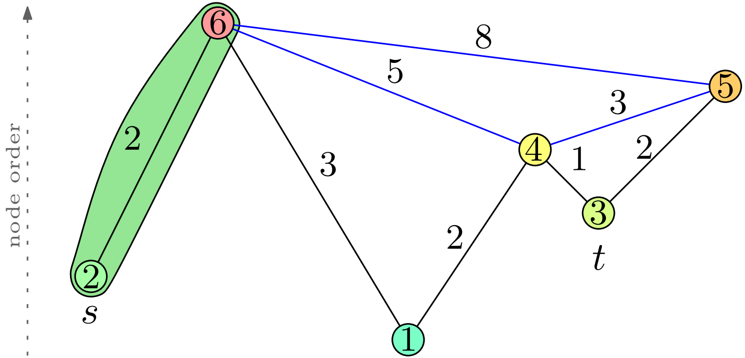

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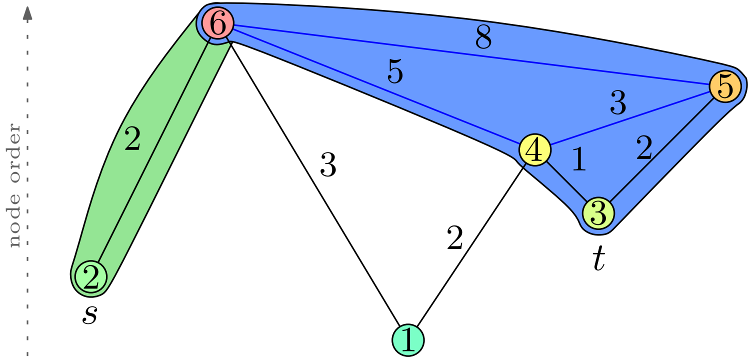

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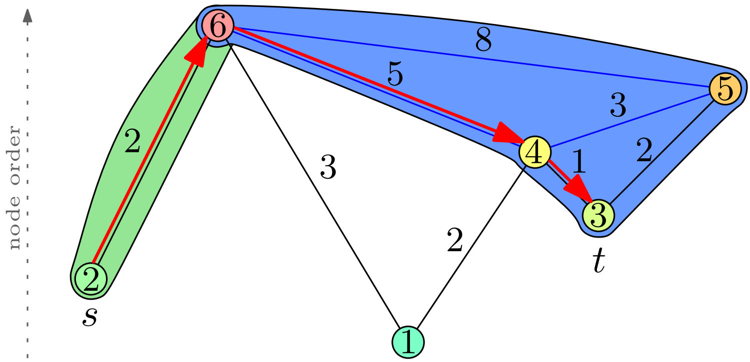
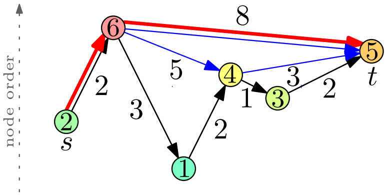
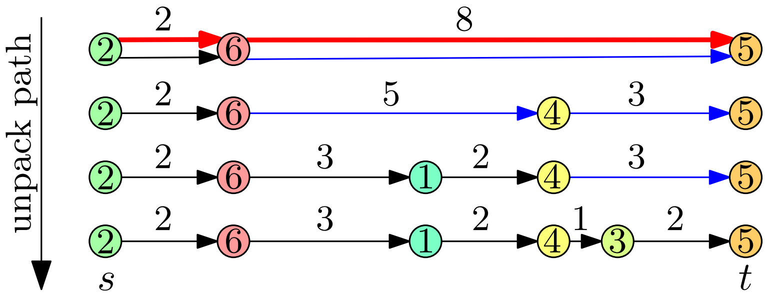


Outputting Paths

- for a shortcut (u, w) of a path $\langle u, v, w \rangle$, store middle node v with the edge
- expand path by recursively replacing a shortcut with its originating edges

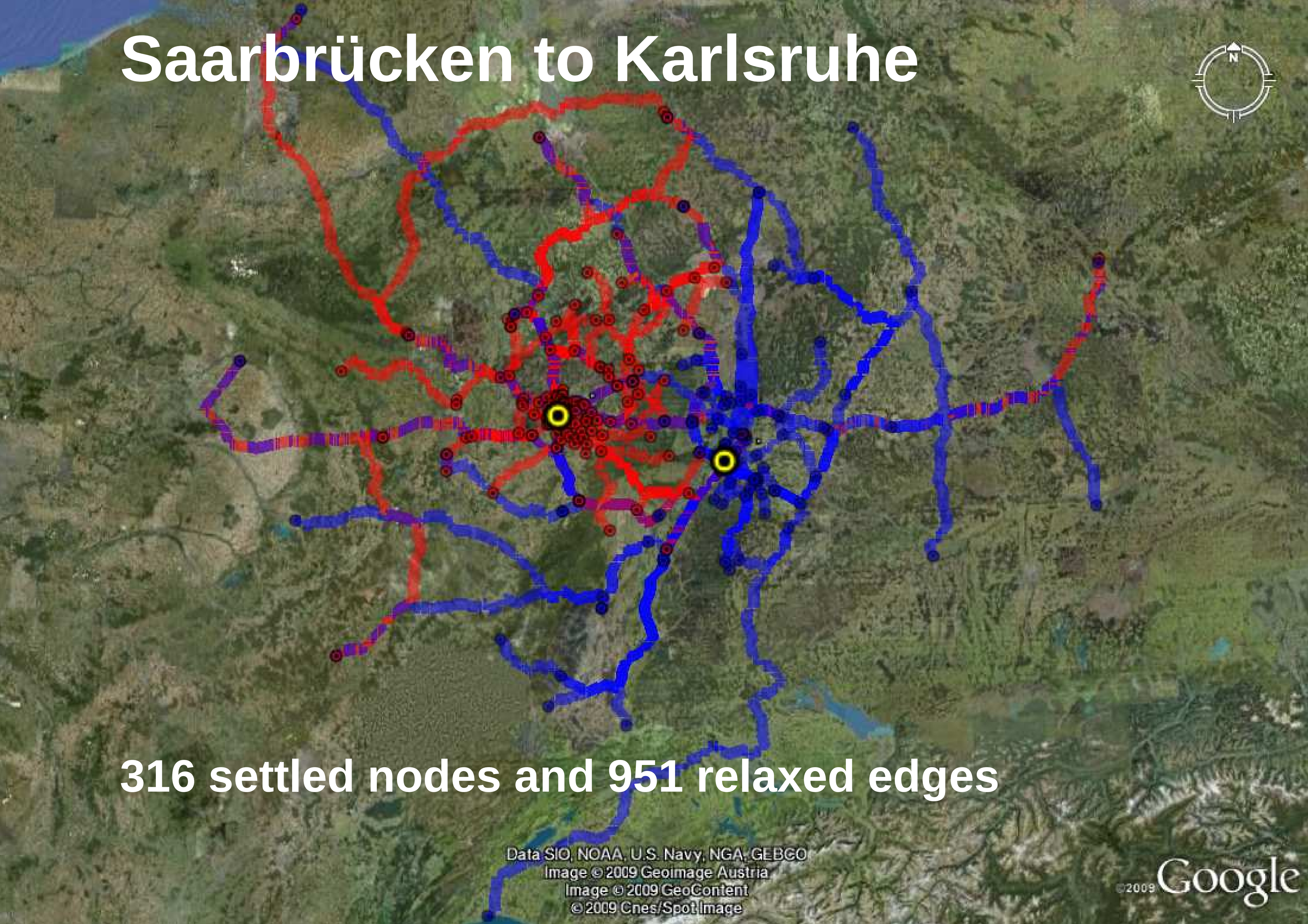




Saarbrücken to Karlsruhe

299 edges compressed to 13 shortcuts.

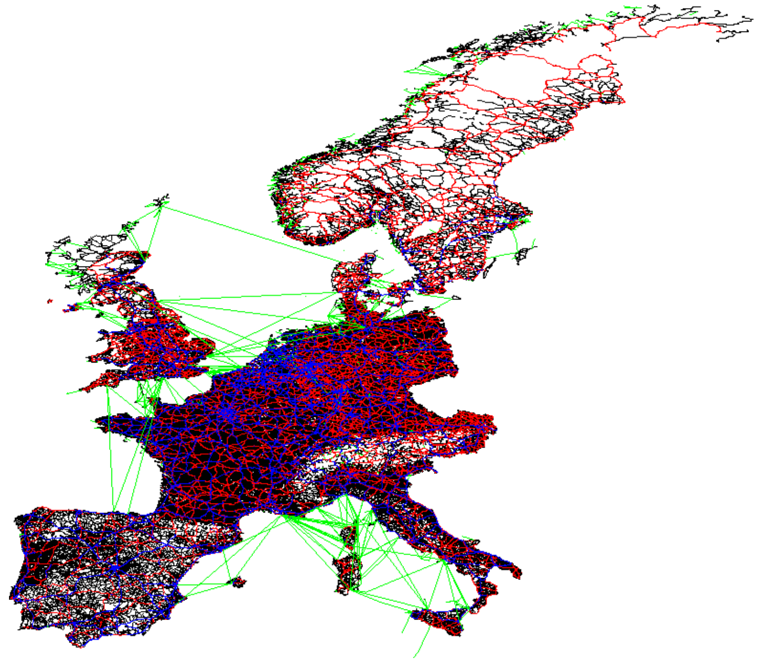
Saarbrücken to Karlsruhe



316 settled nodes and 951 relaxed edges

Contraction Hierarchies

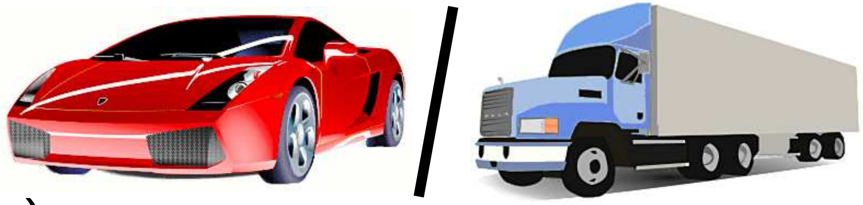
- foundation for our other methods
- conceptually very simple
- handles dynamic scenarios



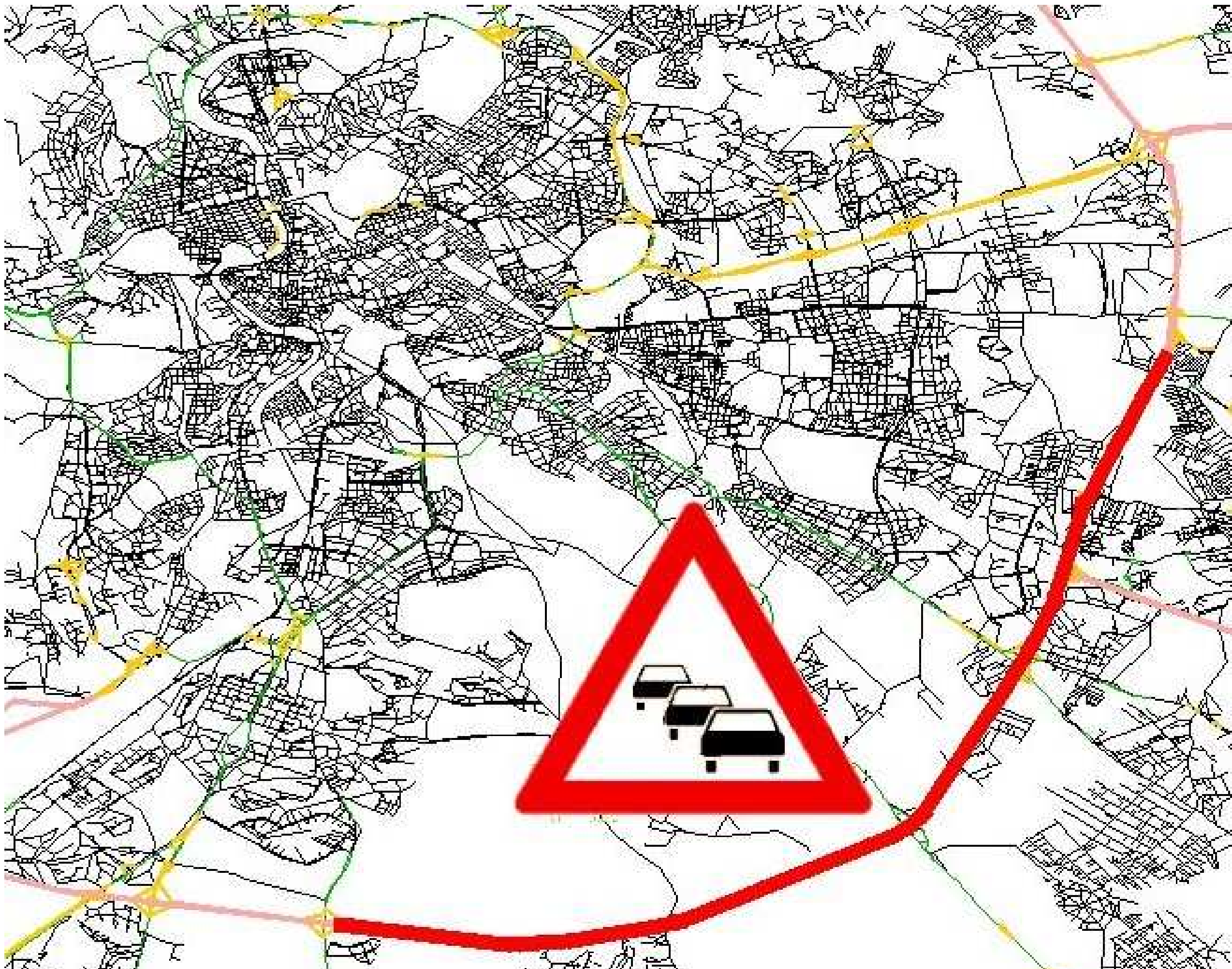
Static scenario:

- 7.5 min preprocessing
- 0.21 ms to determine the path length
- 0.56 ms to determine a complete path description
- little space consumption (23 bytes/node)

Dynamic Scenarios



- change entire cost function
  (e.g., use different speed profile)
- change a few edge weights
  (e.g., due to a traffic jam)



Mobile Contraction Hierarchies

[ESA 08]

- preprocess data on a personal computer
- highly compressed blocked graph representation — 8 bytes/node
- compact route reconstruction data structure — + 8 bytes/node

experiments on a Nokia N800 at 400 MHz

- cold query with empty block cache — 56 ms
- compute complete path — 73 ms
- recomputation, e.g. if driver took the wrong exit — 14 ms
- query after 1 000 edge-weight changes, e.g. traffic jams — 699 ms

Even Faster – Transit-Node Routing

[DIMACS Challenge 06, ALENEX 07, Science 07]

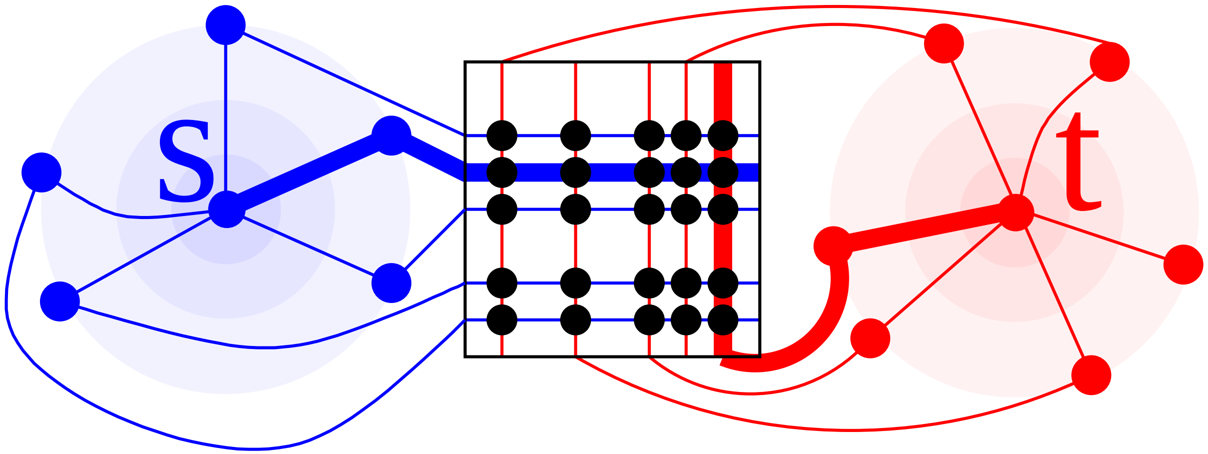
joint work with H. Bast, S. Funke, D. Matijevic

- *very* fast queries

  (down to 1.7 μs, 3 000 000 times faster than DIJKSTRA)

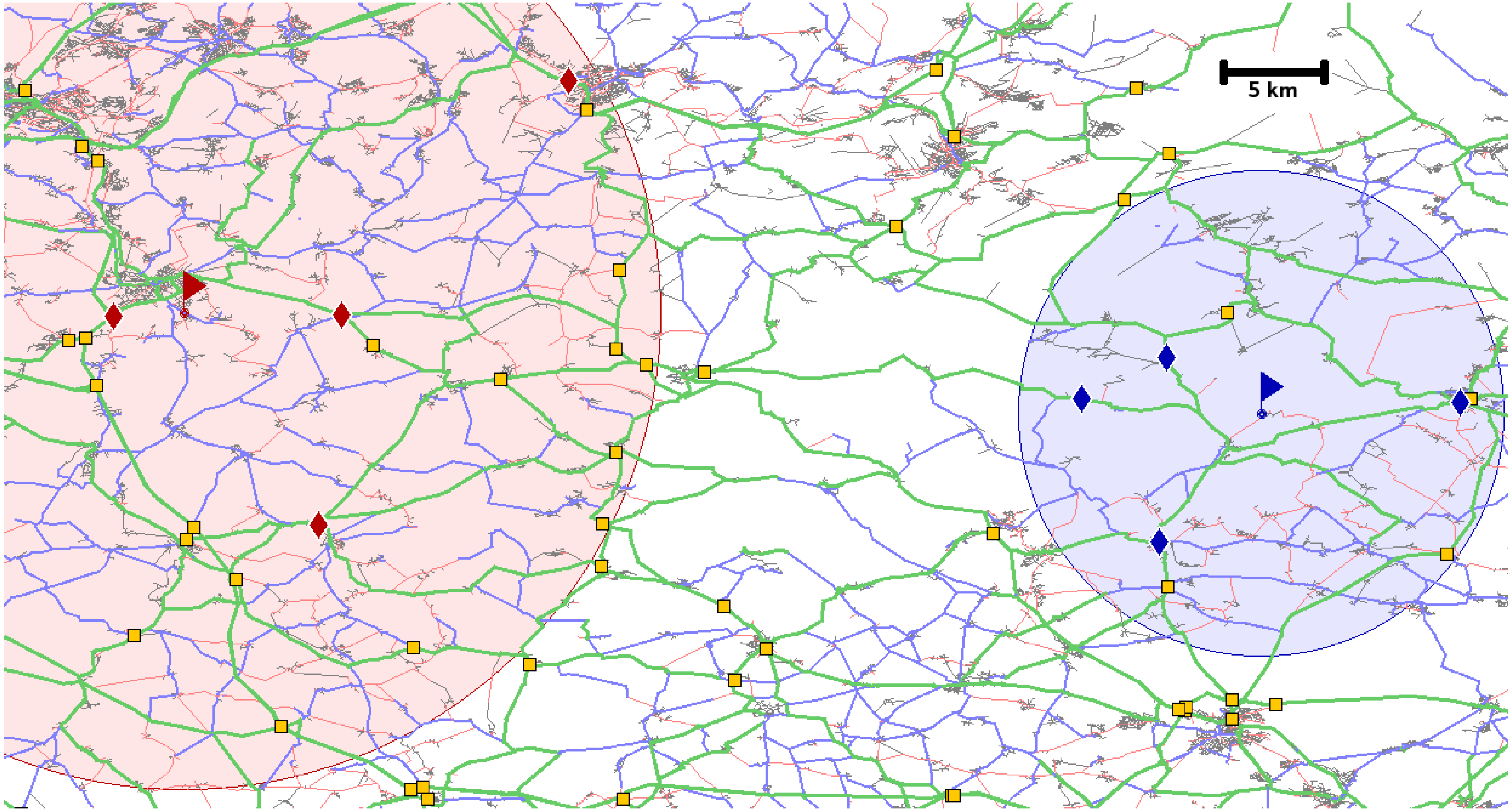
- winner of the 9th DIMACS Implementation Challenge

- more preprocessing time (2:37 h) and space (263 bytes/node) needed



SciAm50 Award

Example

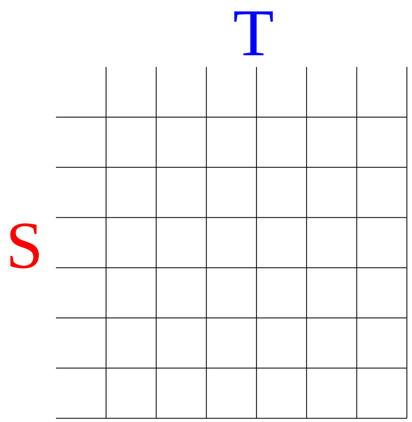


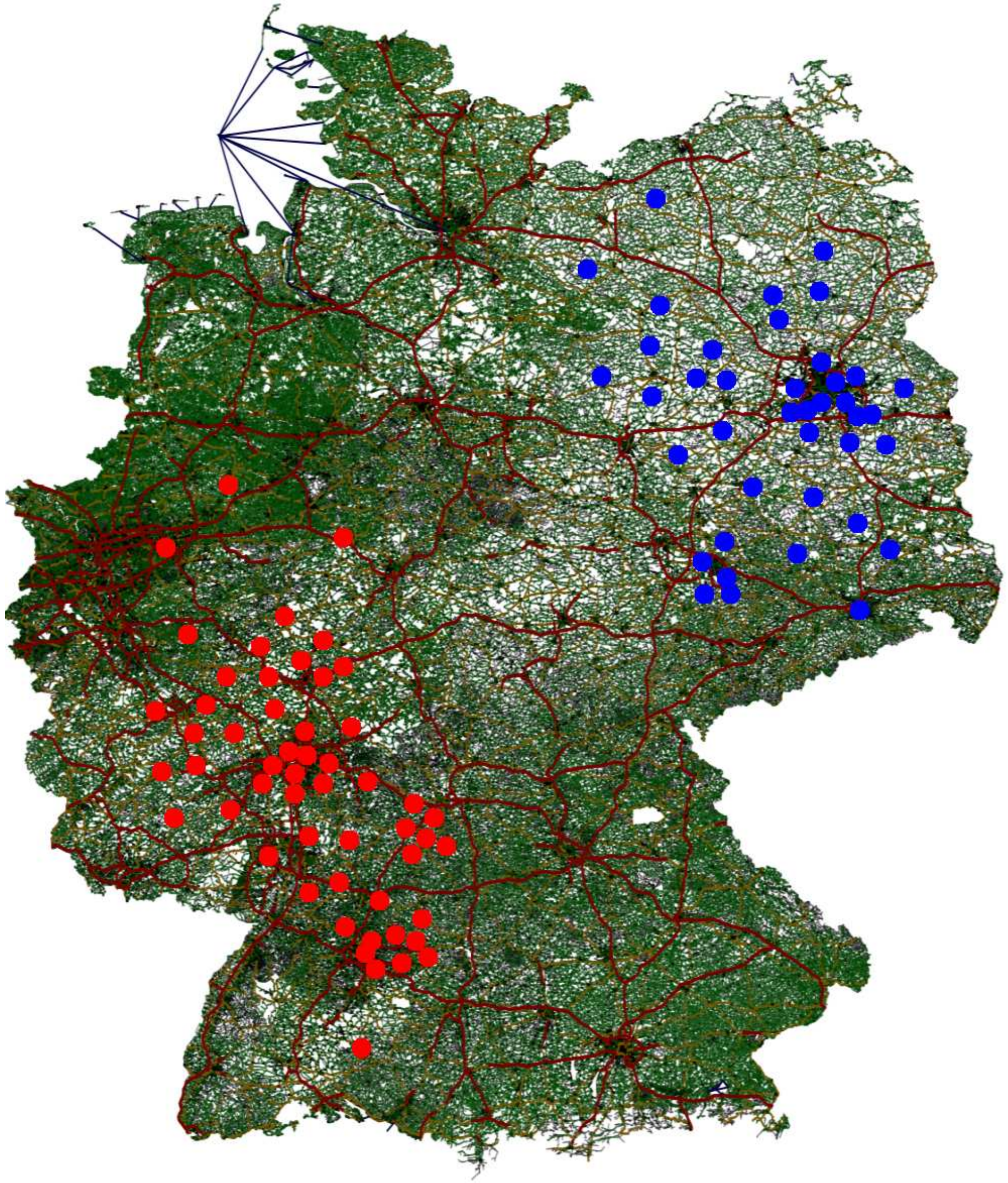
Many-to-Many Shortest Paths

joint work with S. Knopp, F. Schulz, D. Wagner

[ALENEX 07]

- efficient many-to-many variant of hierarchical bidirectional algorithms
- $10\,000 \times 10\,000$ table in 10s





Energy Efficient Routes

Project MeRegioMobil

Moritz Kobitzsch

+DA Sabine Neubauer, PTV

Even more detailed model

(cost-time tradoff

controlled via hourly wage)

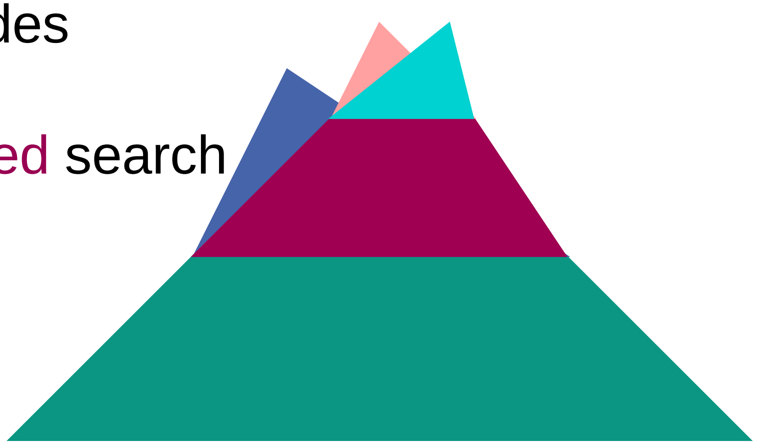
Flexible Objective Functions

Two labels at each edge, e.g., travel time and cost
(mostly ∼energy consumption)

Cost function: arbitrary linear combination

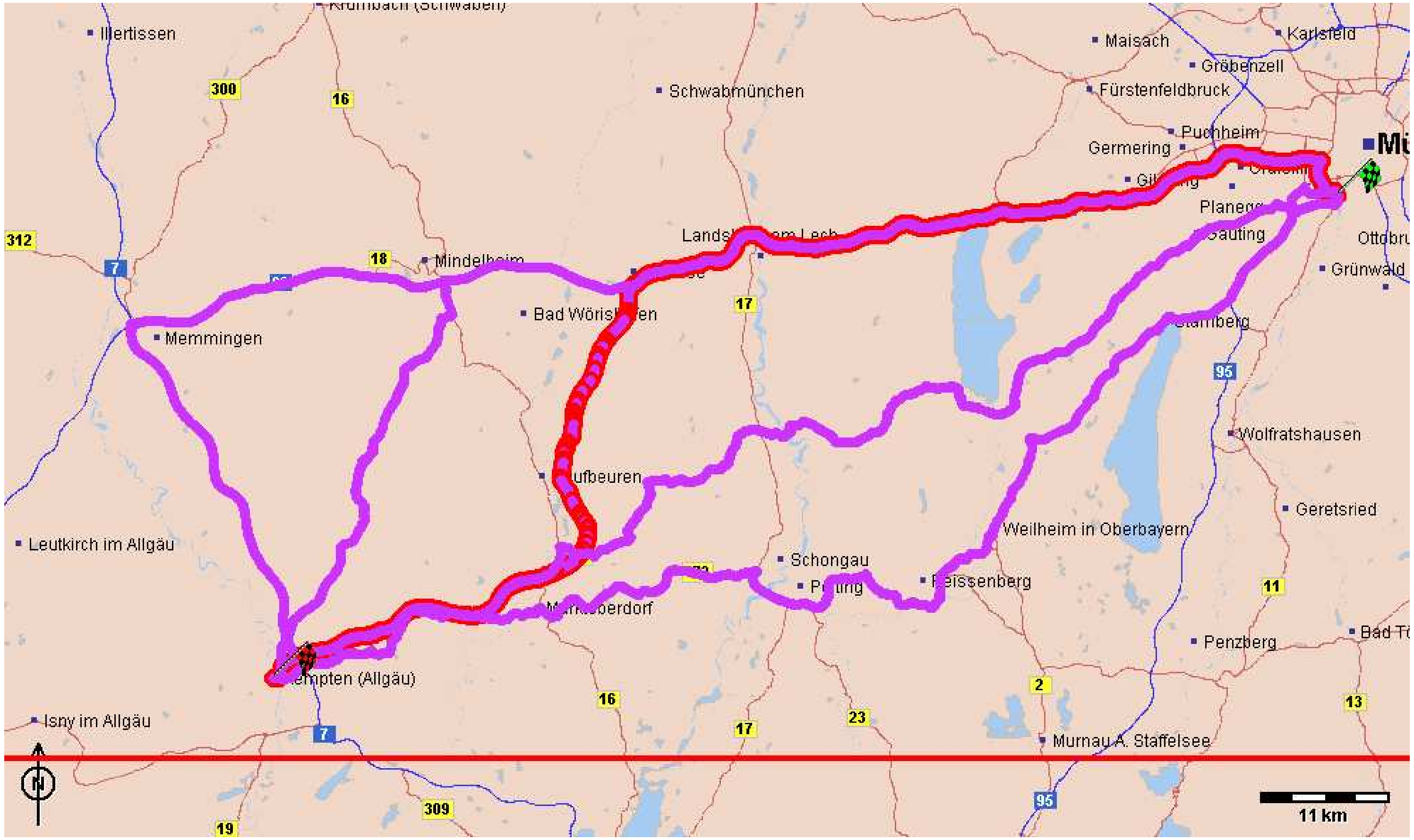
Ideas:

- CHs with valid parameter ranges at each shortcut
- Different node orderings for important nodes
- combine with landmark based goal directed search

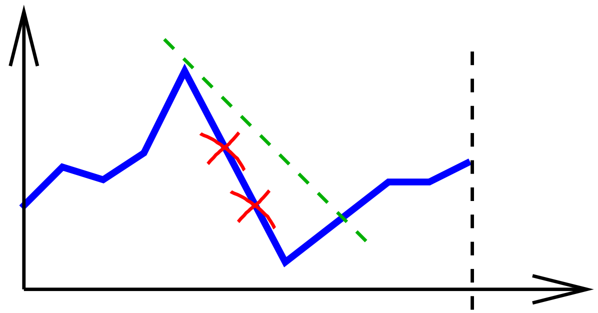


Alternative Routes DA Jonathan Dees, BMW

- What are good alternative route graphs
- Evaluate heuristics for finding them



Time-Dependent Route Planning



- edge weights are travel time functions:
  - {time of day $\mapsto$ travel time}
  - piecewise linear
  - FIFO-property $\Rightarrow$ waiting does not help
- Earliest Arrival Query: (s, t, τ_0)
  $\longrightarrow$ a fastest s–t-route departing at τ_0
- Profile Query:$(s, t, [\tau, \tau'])$
  $\longrightarrow$ fastest travel times departing between τ and tau'.

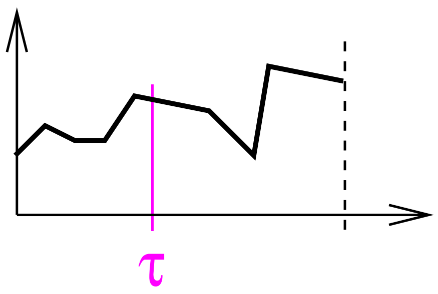
Travel Time Functions

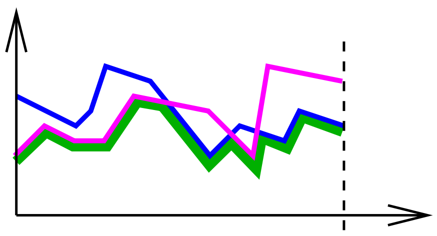
we need three operations

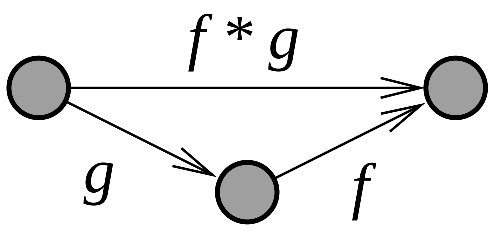
- evaluation: $f(\tau)$ — "$\mathcal{O}(1)$" time
- merging: $\min(f, g)$ — $\mathcal{O}(|f| + |g|)$ time
- chaining: $f * g$ (f "after" g) — $\mathcal{O}(|f| + |g|)$ time

note: $\min(f, g)$ and $f * g$ have $\mathcal{O}(|f| + |g|)$ points each.

$\Rightarrow$ increase of complexity



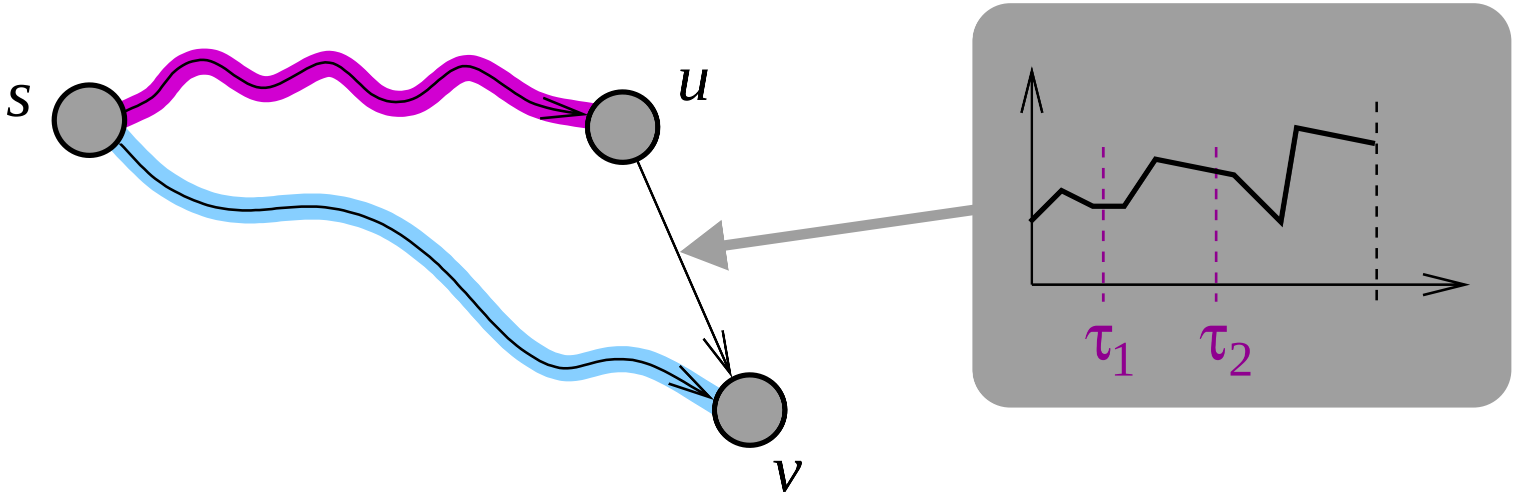




Time-Dependent Dijkstra

Only one difference to standard Dijkstra:

- Cost of relaxed edge (u, v) depends...
- ...on shortest path to u.

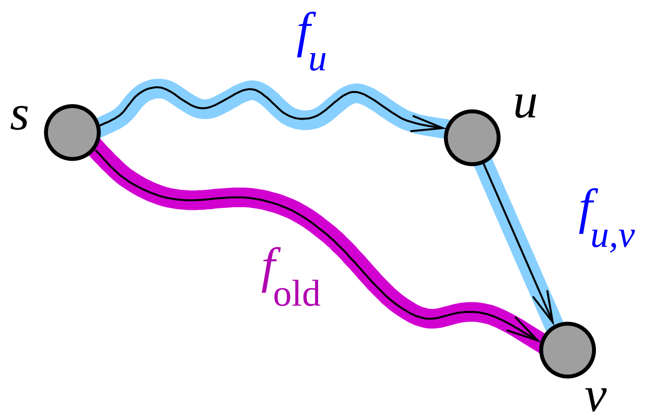


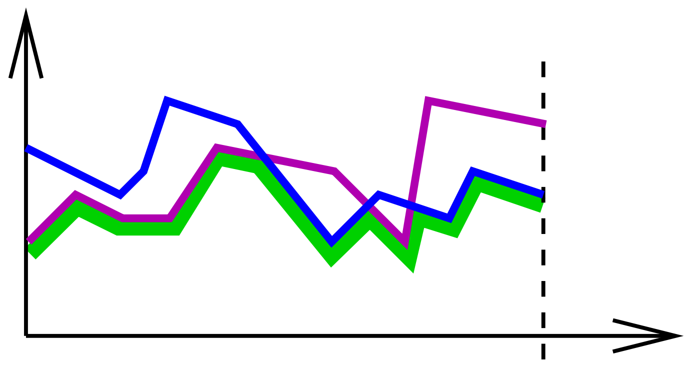
Profile Search

Modified Dijkstra:

- Node labels are **travel time functions**
- Edge relaxation: $f_{\text{new}} := \min(f_{\text{old}}, f_{u,v} * f_u)$
- PQ key is $\min f_u$

$\Rightarrow$ A **label correcting** algorithm

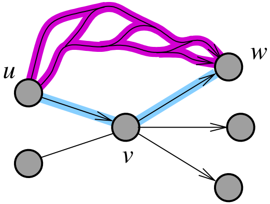


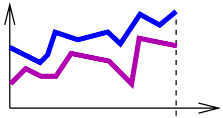


Avoiding Shortcuts

in the time-dependent case

How to know that a shortcut is not needed?





$\Rightarrow$ No shortest path leeds ever over $\langle u, v, w \rangle$

$\Rightarrow$ **Don't insert a shortcut!**

Avoiding Shortcuts

in the time-dependent case

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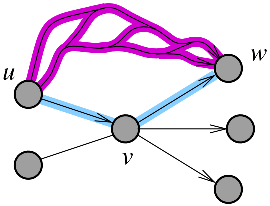
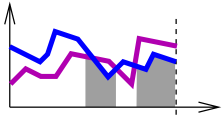




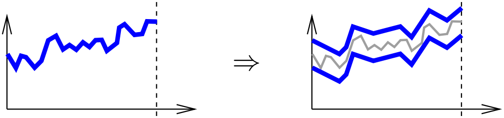
$\Rightarrow$ If a shortest path leeds over $\langle u, v, w\rangle$ for at least one departure time

$\Rightarrow$ **Insert a shortcut!**

ATCH = Approximated TCH

A Space Efficient Data Structure

- **For each edge of the TCH do**
  - Replace weights of shortcuts by two approximated functions...
  - ...an upper bound
  - ...a lower bound
  - ...both with much less points
  - ...lower bound given implicitly by upper bound



⇒ **Needs much less space (10 vs. 23 points).**

Earliest Arrival Queries on ATCHs

Performance

graph	method	ε [%]	space [B/n] ABS	space [B/n] OVH	query [ms]	query SPD	error [%] MAX	error [%] AVG
Earliest Arrival Query								
Germany	TCH	–	994	899	0.72	1 440	0.00	0.00
	ATCH	1	239	144	1.27	816	0.00	0.00
	ATCH	∞	118	23	1.45	714	0.00	0.00
Europe	TCH	–	589	513	1.89	1 807	0.00	0.00
	ATCH	1	207	131	2.47	1 396	0.00	0.00
	ATCH	∞	99	23	15.43	221	0.00	0.00

Profile Queries on ATCHs with Corridor Contraction

Performance

graph	method	ε [%]	space [B/n] ABS	space [B/n] OVH	query [ms]	error [%] MAX	error [%] AVG
Earliest Arrival Query							
Germany	TCH	–	994	899	1 112.04	0.00	0.00
	ATCH	1	239	144	39.23	0.00	0.00
	ATCH	∞	118	23	81.07	0.00	0.00
Europe	TCH	–	589	513	4 308.35	0.00	0.00
	ATCH	1	207	131	468.43	0.00	0.00
	ATCH	∞	99	23	–	–	–

Public Transportation and CHs

Problems:

- Less hierarchy
- Multicriteria a MUST
- complex modelling (walking, changeover delays,. . .)
- prices are not edge based

Approaches:

- SHARC: Contraction + arc flags [Delling et al.]
- Transfer Patterns [Google Zürich]
  $\sim$ transit node routing
- Station-Based CHs [R. Geisberger]
  $\rightsquigarrow$ more complex edge information

Ride Sharing

Current approaches:

- match only ride offers with identical start/destination (perfect fit)
- sometimes radial search around start/destination

Our approach:

- driver picks passenger up and gives him a ride to his destination
- find the driver with the minimal detour (reasonable fit)

Efficient algorithm:

- adaption of the many-to-many algorithm

$\Rightarrow$ matches a request to 100 000 offers in $\approx$ 25 ms

"Ultimate" Routing in Road Networks?

Massive floating car data $\rightsquigarrow$ accurate current situation

Past data $+$ traffic model $+$ real time simulation

$\rightsquigarrow$ Nash euqilibrium predicting near future

time dependent routing in Nashequilibrium

$\rightsquigarrow$ realistic traffic-adaptive routing

Yet another step further

traffic steering towards a social optimum

Summary

static routing in road networks is easy

⇝ applications that require massive amount or routing

⇝ instantaneous mobile routing

⇝ techniques for advanced models

time-dependent routing is fast

⇝ bidirectional time-dependent search

⇝ fast queries

⇝ fast (parallel) precomputation

More Future Work

- Multiple objective functions and restrictions (bridge height,. . .)
- Other objectives for time-dependent travel