Route Planning Algorithms in Transportation Networks

7th International Network Optimization Conference

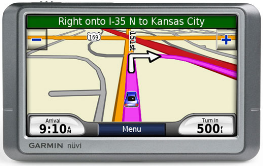
Dorothea Wagner | May 18, 2015, Warsaw, Poland

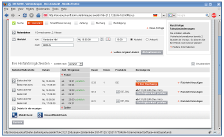
FACULTY FOR INFORMATICS · INSTITUTE FOR THEORETICAL INFORMATICS · CHAIR ALGORITHMICS

Motivation

Important application, e. g.,

- Navigation systems for cars
- Google Maps, Bing Maps, . . .
- Timetable information





Many commercial systems

- Use heuristic methods
- Consider “reasonable” part of the network
- Have no quality guarantees

Find methods for route planning in transportation networks with provably optimal solutions regarding the quality of the routes.

Problem

Request:

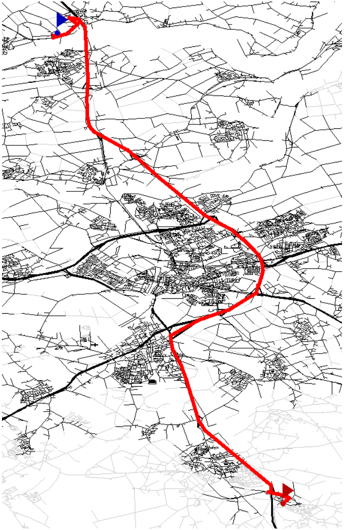
- Find the best connection in a transportation network

Idea:

- Network as graph $G = (V, E)$
- Edge weights are travel times
- Shortest paths in G equal quickest connections
- Classic problem (Dijkstra)

Problems:

- Transport networks are huge
- Dijkstra too slow ($>$ 1 second)



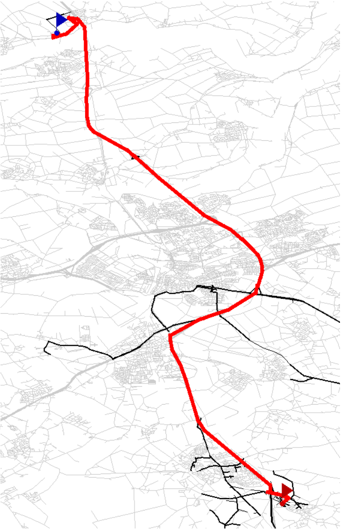
Speed-Up Techniques

Observations:

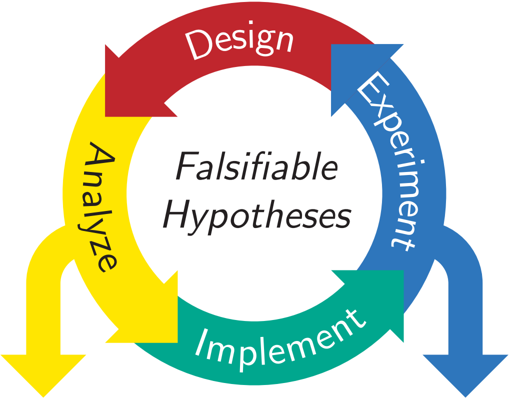
- Dijkstra visits all nodes closer than the target
- Unnecessary computations
- Many requests in a hardly changing network

Idea:

- Two-phase algorithm:
  - Offline: compute additional data during preprocessing
  - Online: speed-up query with this data
- 3 criteria: preprocessing time and space, speed-up over Dijkstra



Showpiece of Algorithm Engineering



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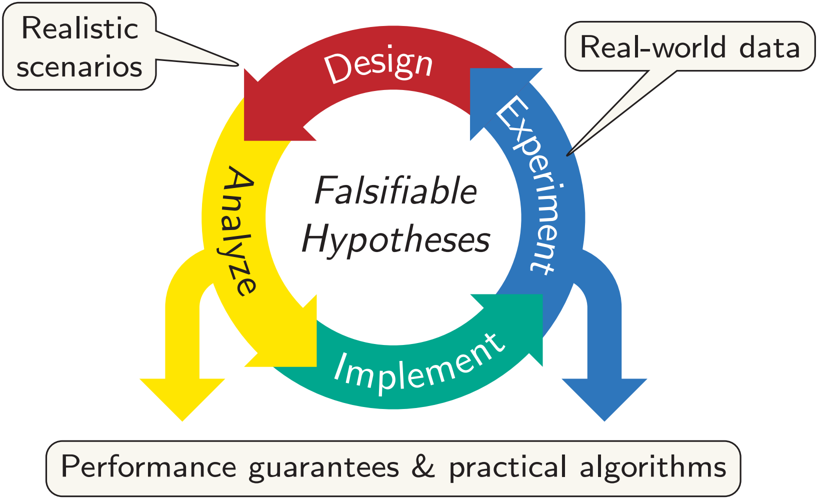

History I

Phase I: Theory (1959 - 1999):

- Improve theoretical worst-case running time
- By introduction of better data structures
- Bidirectional search, A^*-search (goal-directed)

Phase II: Speed-up techniques (1999 - 2005):

- Two approaches: goal-directed and hierarchical approach
- Improvement on this for several inputs

Phase III: Road networks (2005 - 2008):

- Focus on continent-sized road networks
- DIMACS challenge in 2006
- Speed-up factors in range of several millions over Dijkstra

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History II

Phase IV: Towards more realistic scenarios (2008-2012):

- Time-dependency, multicriteria, alternative routes, ...
- Timetable information
- Back to theory: why do things work?

Now: New challenges (since 2012):

- Other metrics, e. g., energy consumption
- Customizability (supporting user-centric route planning)
- Multimodal

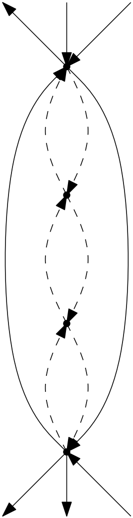
Speed-Up Techniques

Many techniques:

- Arc-Flags [Lau04]
- Multi-Level Dijkstra [SWW00, HSW08]
  - Customizable Route Planning (CRP) [DGPW11]
- ALT: A*, Landmarks, Triangle Inequality [GH05, GW05]
- Reach [GKW07]
- Contraction Hierarchies (CH) [GSSD08]
- Transit Node Routing (TNR) [ALS13]
- Hub Labeling (HL) [ADGW12]
- ...

Shortcuts

[SWW99, SS05, GSSD08]



Observation:

- Nodes with low degree are not important

Contract graph

- Iteratively remove such nodes
- Add shortcuts to preserve distances between non-removed nodes

Query:

- Bidirectional
- Prune edges heading to less important nodes

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Contraction Hierarchies [GSSD08]

Idea: solely use contraction

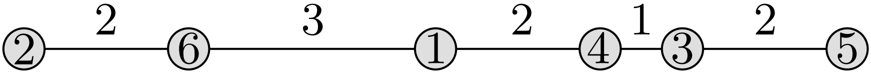
Approach:

- Heuristically order nodes by “importance”
- Contract nodes in that order
- Node v contracted by

forall the *edges* (u, v) *and* (v, w) **do**
  if (u, v, w) *unique shortest path* **then**
    add shortcut (u, w) with weight $\text{len}(u, v) + \text{len}(v, w)$;

- Query only looks at edges to more important nodes

Example: CH Preprocessing



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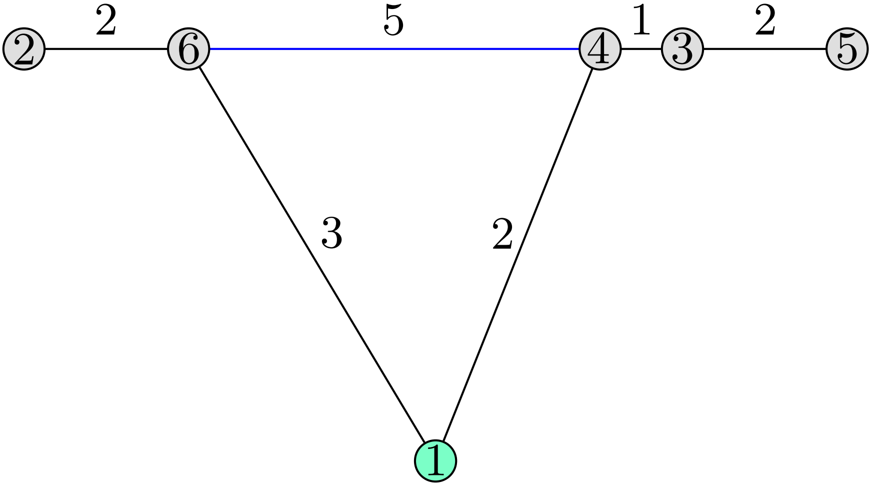

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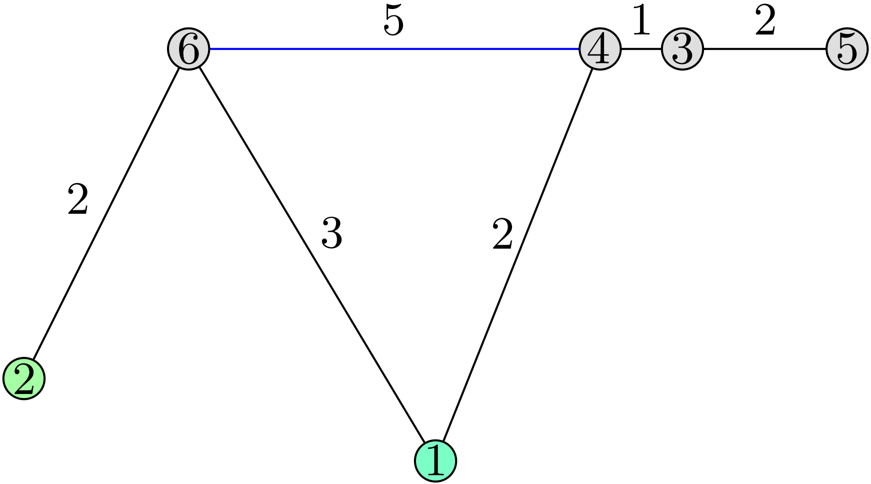

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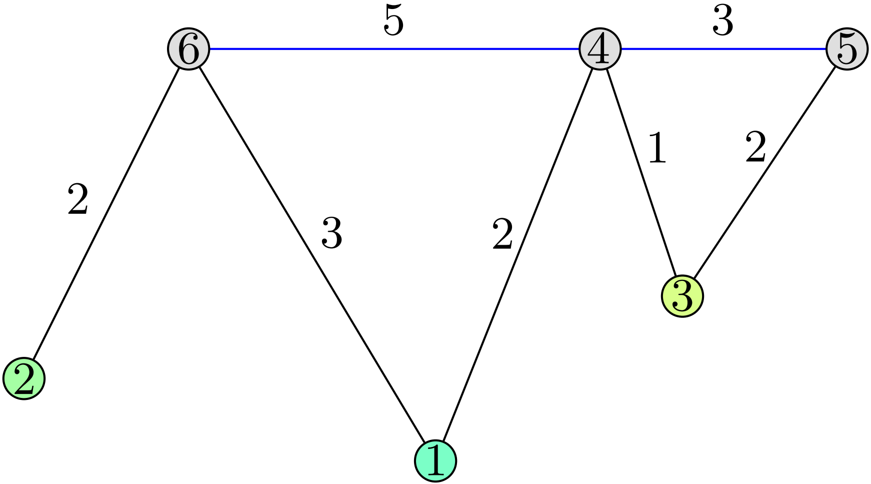

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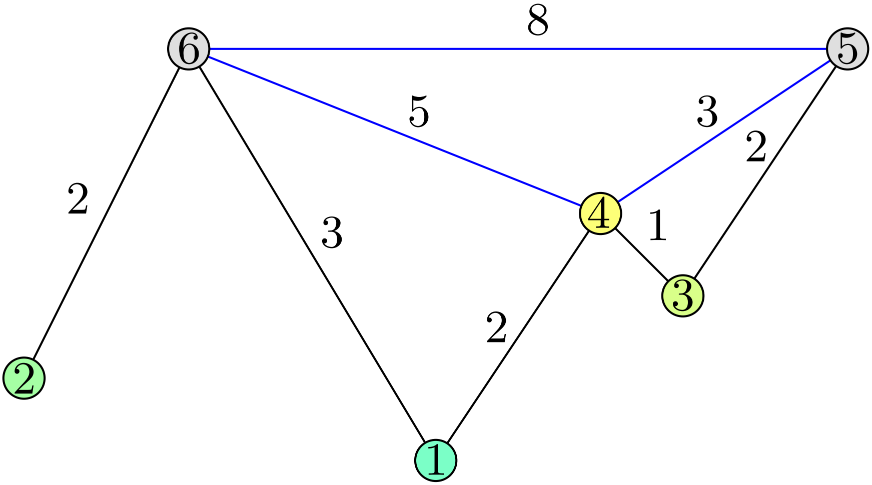

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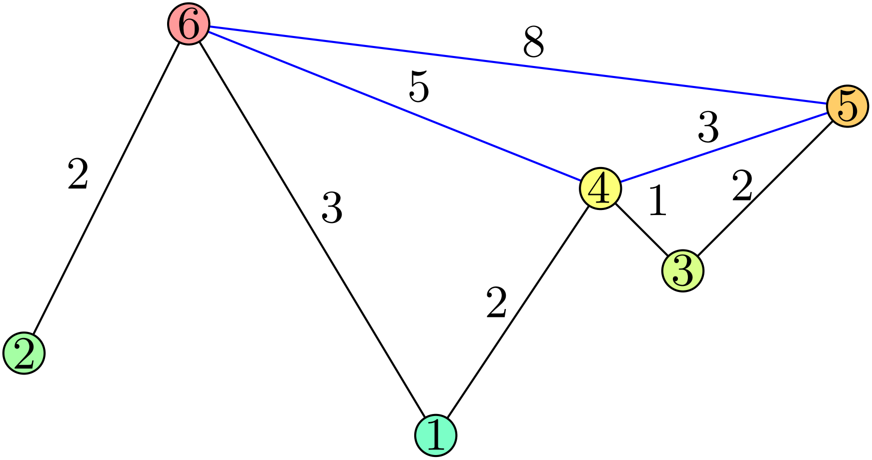
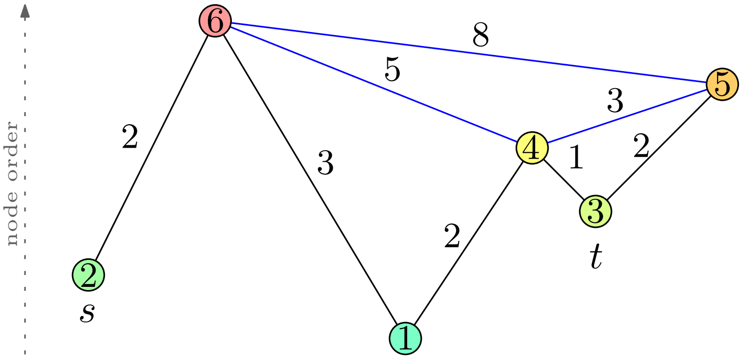


CH Query

- Modified bidirectional Dijkstra
- 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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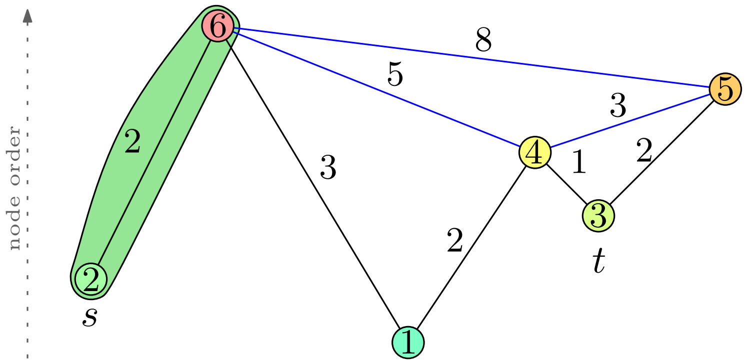

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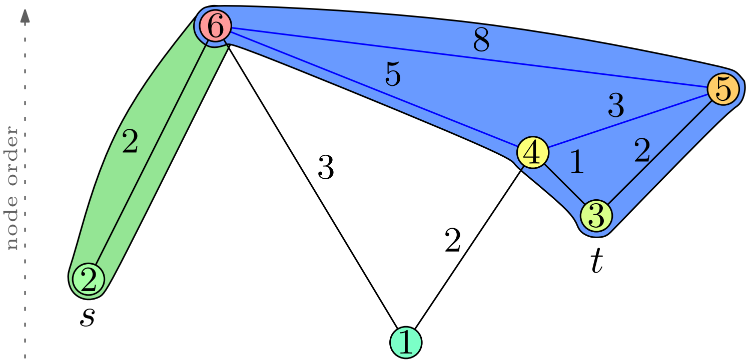

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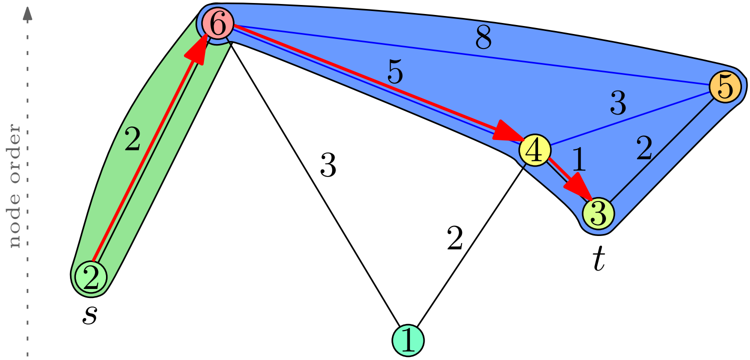

From Practice to Theory: WeakCH

Question: What is a good contraction order?

- No guarantees on search space [GSSD08]

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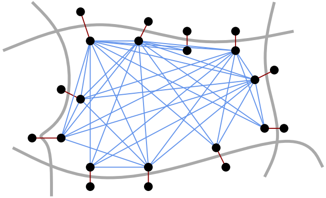
WeakCH [BCRW13]

- Balanced separator nodes are important
  $\rightarrow$ resulting CH is called *weak*
- $O(n^\alpha)$ separators $\rightarrow$ $O(n^\alpha)$ nodes in the search space
- Order is independent of metric

(Multi-Level) Overlays [SWW00, HSW08]

Observation: many (long-distance) paths share large subpaths
Idea: precompute partial solutions

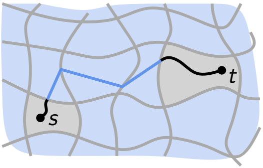


Overlay graph:

- Select important nodes (separators, path coverage, heuristic)
- Compute shortcut-edges:
  - Skip unimportant nodes
  - Conserve distances to important nodes

Queries:

- Multi-level Dijkstra variant
- Ignore edges towards less important nodes

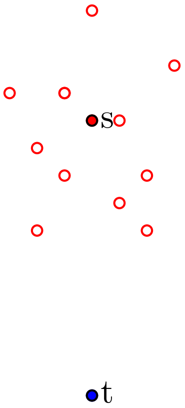


analogous: hierarchies with several levels of nodes of varying importances

Hub Labeling

Preprocessing:

- For each node u, compute label $L(u)$
  - A set of hub nodes v and their distance $\mathrm{dist}(u, v)$ to u



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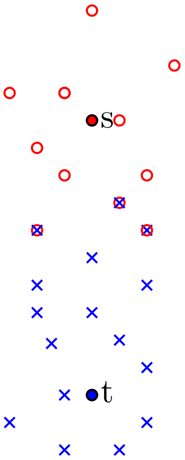
  for every s, t-pair, the shortest path goes through the intersection of $L(s) \cap L(t)$



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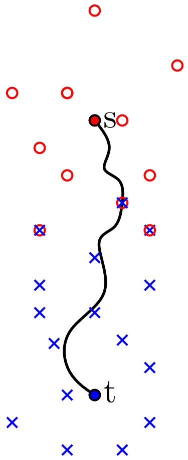

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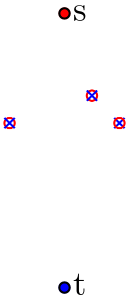

***s*–*t* query:**

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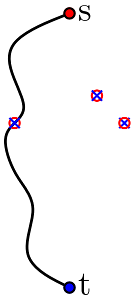

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- Find node $v \in L(s) \cap L(t) \ldots$
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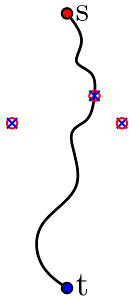

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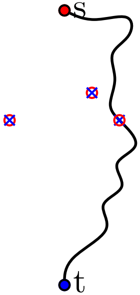

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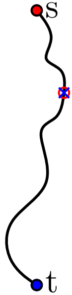

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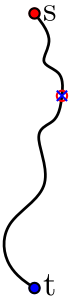

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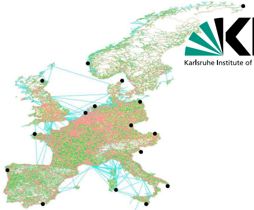
Observations:

- Very simple query (can even be implemented in SQL)
- Query performance depends only on label sizes
- The “magic” lies in computing a small labeling efficiently

Experimental Evaluation



Input: Road network of Europe

- Approx. 18M nodes
- Approx. 42M edges

	Preprocessing		Query	
Algorithm	Time [h:m]	Space [GiB]	Time [μs]	Speedup
Dijkstra [Dij59]	—	—	2 550 000	—
ALT [GH05, GW05]	0:42	2.2	24 521	104
CRP [DGPW11]	1:00	0.5	1 650	1 545
Arc-Flags [Lau04]	0:20	0.3	408	6 250
CH [GSSD08]	0:05	0.2	110	23 181
TNR [ALS13]	0:20	2.1	1.25	2 040 000
HL [ADGW12]	0:37	18.8	0.56	4 553 571

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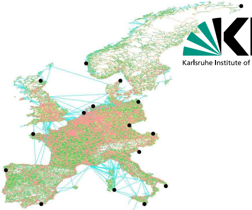

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In use at Bing, Google, TomTom, …

New Challenges

More realistic metrics:

- Turn costs, electro mobility
- Points of interests
  (nearest POIs, shortest via-POIs)
- User customizable metrics
  e.g., height restrictions, avoid freeways, eco-friendliness, . . .
- Fast customization time per metric
- Very small space overhead

Multimodal networks:

- Change the type of transportation during the journey
- Allow only “reasonable” transfers
- Several constraints to the shortest path
- Multicriteria

Route Planning for Electric Vehicles

Electric vehicles:

- Future means of transportation
- Run on regenerative energy sources

But:

- Restricted battery capacity
- Long recharging times
- “Range anxiety”

$\Rightarrow$ Consider energy consumption in route planning applications

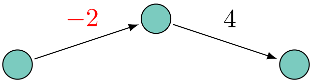
Task: Given start and destination in a road network,
find the route that minimizes energy consumption.

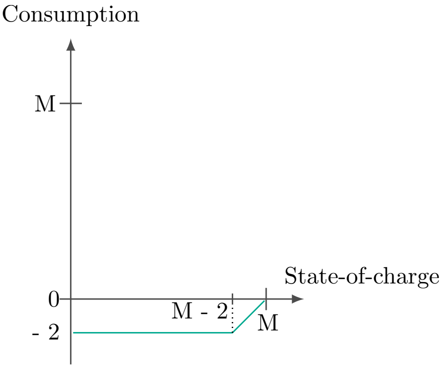
Energy-Optimal Routes

Challenges:

- Negative edge weights (recuperation)
- Battery constraints (no over-, undercharging)

Energy consumption depends on battery state-of-charge (at the start):





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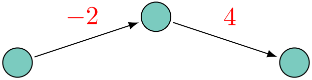

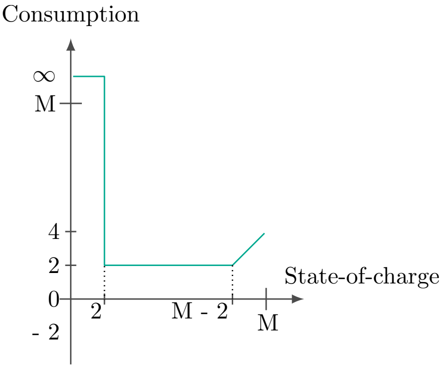

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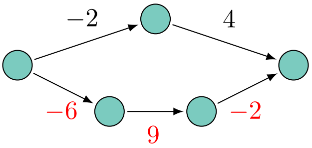

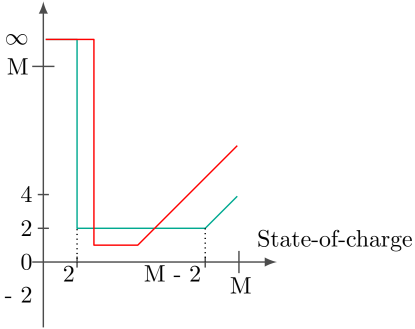

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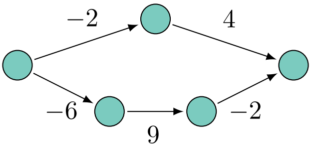
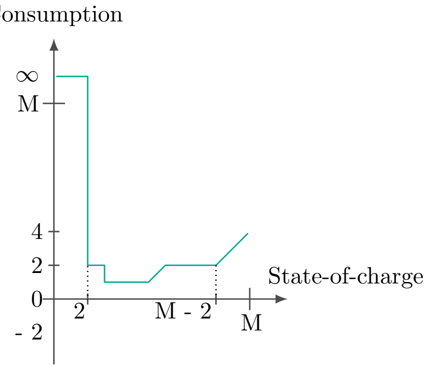




Energy-Optimal Routes [BDPW13, BDHS+14]

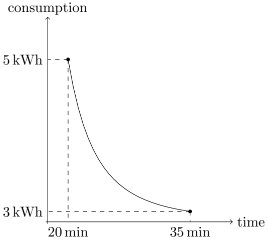
Requirements for speedup techniques:

- Shortcuts are functions, not scalar values
- User-dependent consumption profiles ($\Rightarrow$ custom metrics)

Experiments:

- Energy-optimal paths: 63 % extra time
- Fastest paths: 62 % extra energy

$\Rightarrow$ Energy-optimal routes: follow slow roads



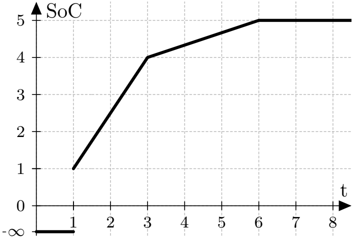
Trading travel time for energy consumption:

- Consider constrained paths
  - E.g., find the fastest path such that the battery does not run out
  - $\mathcal{NP}$-hard
- Energy can be saved driving below speed limit
- Additional instructions to the driver

Including Charging Stops

Task: Find the fastest path such that the battery does not run out.

- Recharging allowed at some nodes (but requires charging time).
- Realistic models of charging stations:
  - Charging power varies
  - Super chargers
  - Battery swapping stations



Approach:

- Extension of bicriteria search
- Propagates charging functions
- CHArge: Combination with CH and A*
  - Optimal routes in seconds / minutes
- Heuristic approaches (based on CHArge)
  - Near-optimal solutions in well below a second

Custom Metrics

Karlsruhe Institute of Technology

Problem

- Preprocessing is metric-dependent
- State-of-the-art algorithms tailored to travel time
  heavily exploit 'hierarchy' of road categories

Naive solution

- Compute preprocessing for each metric, e. g.
  - Distance
  - Pedestrian
  - Travel time, but don't use toll roads
  - Travel time, avoid left turns, height restrictions, avoid tolls, . . .
- Preprocessing and query time increase significantly
- Higher space overhead

From Theory to Practice: Customizable Contraction Hierarchies [DSW14]

Idea:

- CH topology is the same regardless of metric
- Quickly introduce new metric

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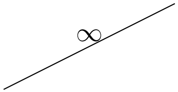

an edge in the CH

From Theory to Practice: Customizable Contraction Hierarchies [DSW14]

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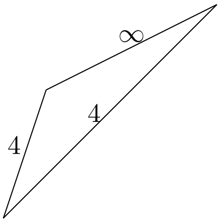

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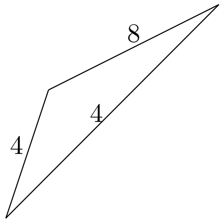

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Karlsruhe Institute of Technology

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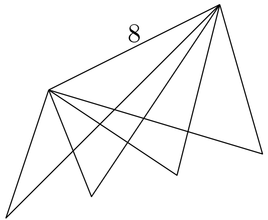

do this for all lower triangles

What is a Timetable?

Karlsruhe / 10 min

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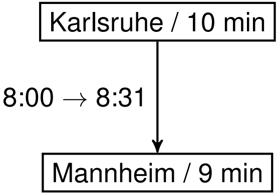
What is a Timetable?



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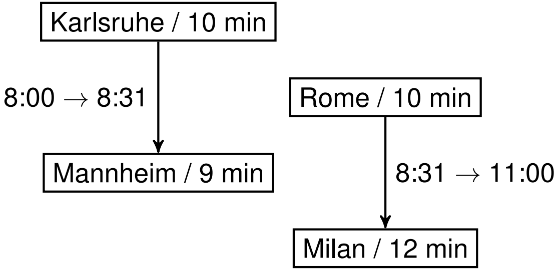

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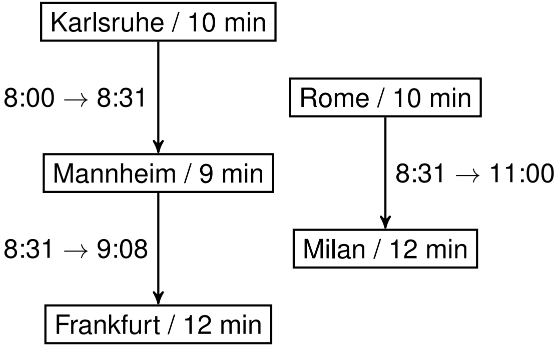

Existing Approaches

list of connections and stops

query

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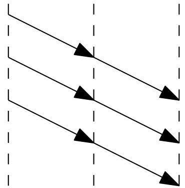
Existing Approaches

list of connections and stops



Time Expanded
[PSWZ08]

query

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Existing Approaches

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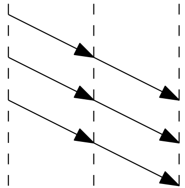

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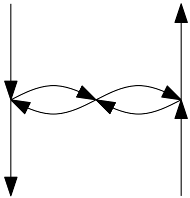
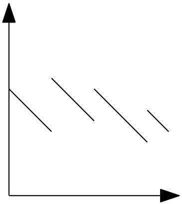


Time Dependent
[PSWZ08]



complex arc weights

query

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Existing Approaches

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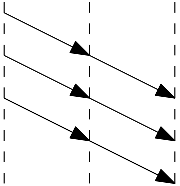

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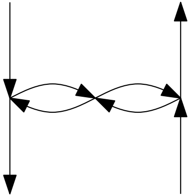
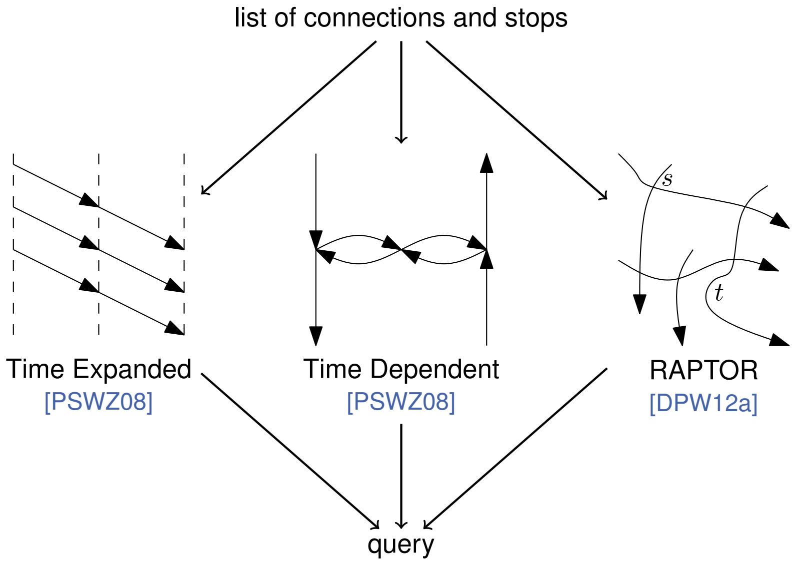


Time Dependent
[PSWZ08]

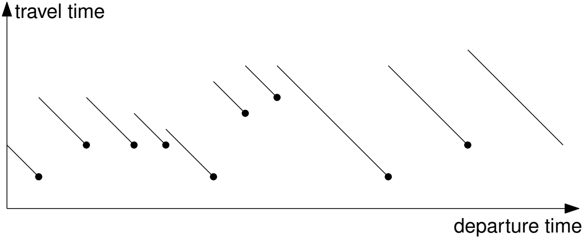
query

Existing Approaches



Timetable Queries

- Inherently time-dependent: discrete departure times
- More query scenarios:
  - Depart now: earliest arrival time?
  - Depart later: shortest travel time?
  - Profile queries: set of journeys with varying departure times
  - Multicriteria: number of transfers, price, ...
- Different network structure: less hierarchical, less well-separated, very different schedules at night, ...



Connection Scan (CSA) [DPSW13]

Output: earliest arrival time
Input: timetable, source stop, source time, target stop

stop ID		0	1	2	3	4	
earliest arrival time	$\cdots$	$+\infty$	$+\infty$	$+\infty$	$+\infty$	$+\infty$	$\cdots$

elementary connections ordered by departure time	$\cdots$	dep.stop	arr.stop	dep.time	arr.time		dep.stop	arr.stop	dep.time	arr.time		dep.stop	arr.stop	dep.time	arr.time		$\cdots$

*missing in the example: footpaths and minimum change times

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Connection Scan (CSA) [DPSW13]

Output: earliest arrival time
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stop ID		0	1	2	3	4	
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elementary connections ordered by departure time				
…				
dep: 1	arr: 3	9:00	9:25	
dep: 3	arr: 4	9:15	9:45	
dep: 3	arr: 4	9:40	9:55	
…				

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Connection Scan (CSA) [DPSW13]

Output: earliest arrival time
Input: timetable, source stop, source time, target stop

stop ID		0	1	2	3	4	
earliest arrival time	…	$+\infty$	8:00	$+\infty$	$+\infty$	$+\infty$	…

elementary connections ordered by departure time				
…				
dep: 1	arr: 3	9:00	9:25	
dep: 3	arr: 4	9:15	9:45	
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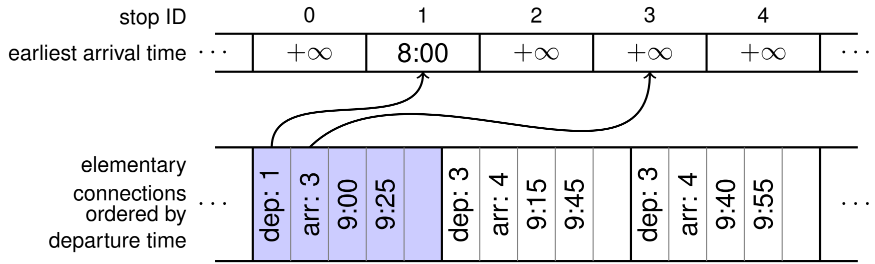

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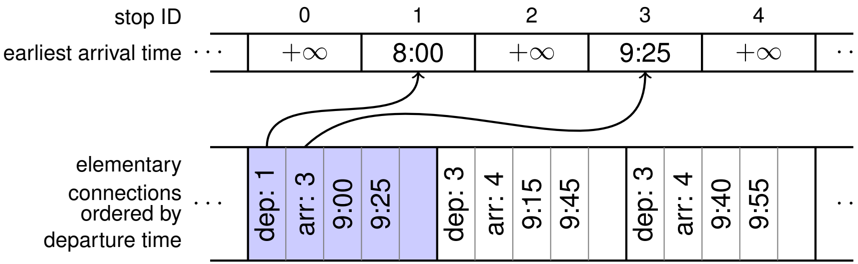

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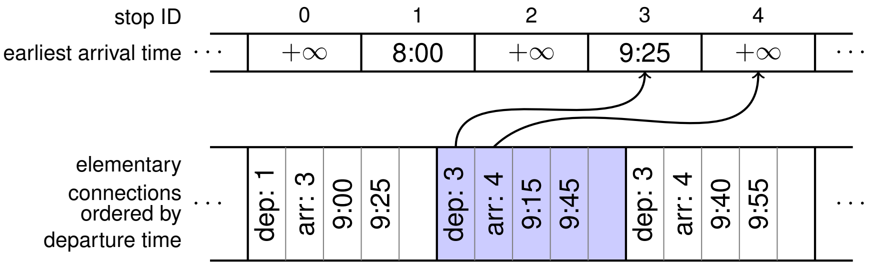

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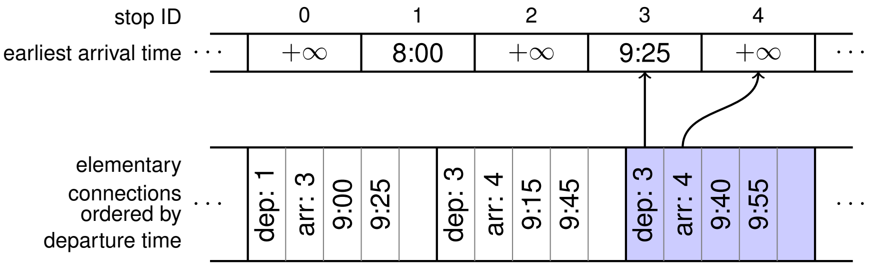

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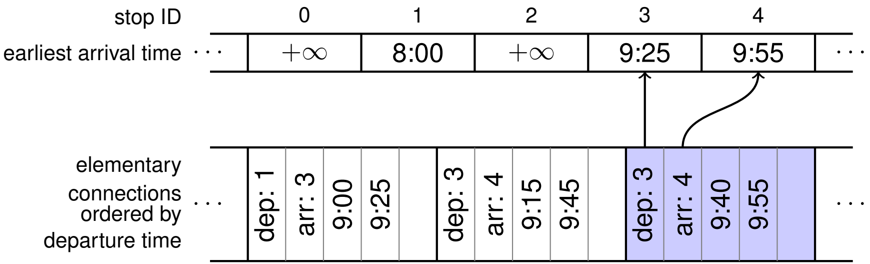

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elementary connections ordered by departure time																
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*missing in the example: footpaths and minimum change times

time table graph is a DAG
faster than Dijkstra, better use of modern processor architectures

Experimental Evaluation

Karlsruhe Institute of Technology

Input: timetable

- London: 5 M connections, 21 k stops
- Germany: 46 M connections, 252 k stops

	Algorithm	Time [ms]	speed-up.
London	TE Dijkstra [PSWZ08]	44.8	—
	TD Dijkstra [PSWZ08]	10.9	4.1
	CSA [DPSW13]	1.8	24.9
DE	TE Dijkstra [PSWZ08]	2960.2	—
	CSA [DPSW13]	298.6	9.9
	CSAccel [SW14]	8.7*	340.2

Intel Xeon E5-2670, 2.6 GHz, 64 GiB DDR3-1600 RAM, 20 MiB L2 cache

*preprocessing: 30 min, 256.4 MiB

Navigation Device for the World

Worldwide network composed of car, rail, flight, . . .

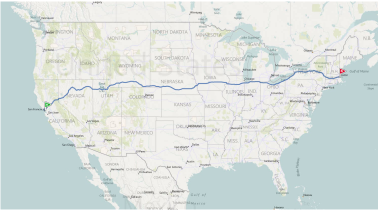
Multimodal Routing

Up to now:

- Restricted to one transportation network
- Time-independent and time-dependent (separately)

What we really want is planning a journey by

- Choosing source and destination
- Desired means of transportation (car, train, flight, . . .)
- . . . in a mixed network



Adapting Speed-Up Techniques

[Paj09], [KLPC11]

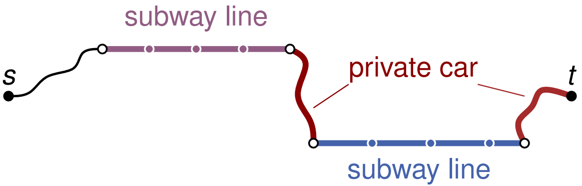
- **Bidirectional search**
  easily adaptable (time-dependency is hard)
- **Goal-directed search**
  ALT adaptable but low speed-ups,
  Arc-Flags turns out difficult
- **Contraction**
  adaptable with some restrictions
  - Contracted graph is called the **Core**

two promising approaches:

- **Access-node routing (ANR)**
  adapting ideas from transit-node routing (table lookups)
- **User-constrained CH (UCCH)**
  augmenting contraction hierarchies

Multiple Transportation Modes

Problem: Unrestricted journeys allow arbitrary transfers



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Multiple Transportation Modes

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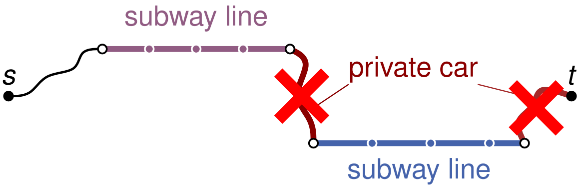

- Not all sequences of transportation modes are reasonable

Multiple Transportation Modes

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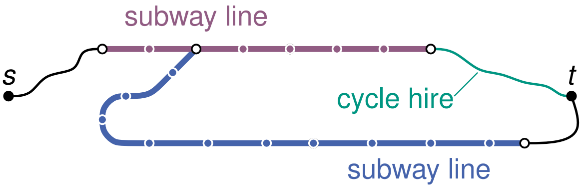
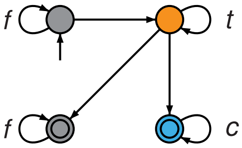


- Not all sequences of transportation modes are reasonable
- Preferred mode of transport varies between users

Solution

"Label Constrained Shortest Path Problem" (LCSPP)

- Define alphabet of transportation mode
- Finite-state automaton describes sequences of vehicles
- Every path must fulfill the requirements imposed by the automaton



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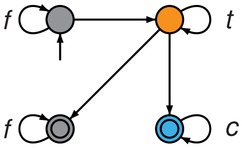

Algorithms for LCSPP

- Dijkstra on the product graph with the automaton works but is slow [BJM00]
- Speed-up techniques: ANR [DPW09], SDALT [KLPC11]
- Automaton as input during the query: UCCH [DPW12b]

User-constrained CH (UCCH) [DPW12b]

Multimodal CH:

- Contraction introduces shortcuts with label sequences
- Witness search depends on constraints
  requires a-priori knowledge of the constraint automata

Idea: do not contract nodes with incident link-edges.

- Contraction and witness search are limited to each modality

$\Rightarrow$ Preprocessing independent of mode sequence constraints

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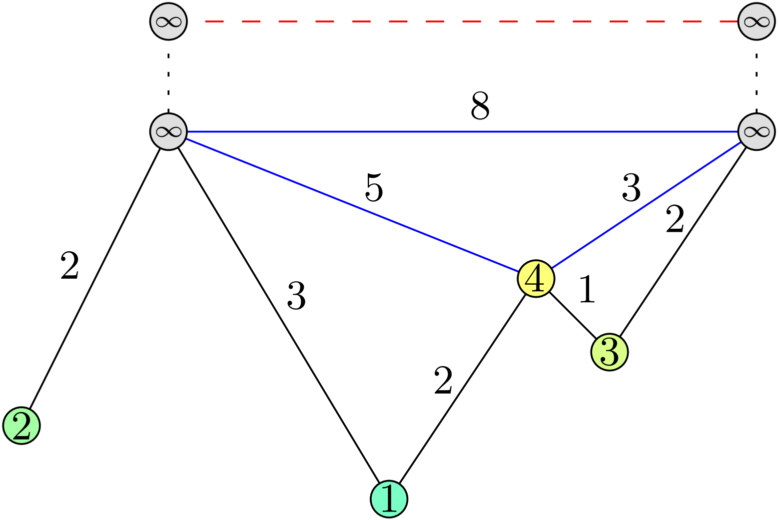
Example: UCCH Preprocessing



UCCH

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Preprocessing

- Linked nodes are not contracted thus contained in the core
- Shortcuts between core nodes preserve distances
  allows using the road network between rail stations

Query

- CH search on the component
- Label constrained search on the core
- Engineering yields further improvement

Experimental Evaluation

Networks:
road: europe & north america (50 M nodes, 125 M edges)
train: europe (31 k stops, 1.6 M connections)
flight: Star Alliance (1 172 airports, 28 k connections)

		Preprocessing		Query	
	Algorithm	Time [h:m]	Space [MiB]	Time [ms]	Speedup
road & flight	Dijkstra	—	—	33 862	1
	ANR [DPW09]	3:04	14 050	1.07	31 551
	UCCH [DPW12b]	1:18	542	0.67	50 540
all three	Dijkstra	—	—	35 261	1
	ANR [DPW09]	—	—	—	—
	UCCH [DPW12b]	1:27	558	70.52	500

Intel Xeon E5430, 2.66 GHz, 32 GiB RAM, 12 MiB L2 cache

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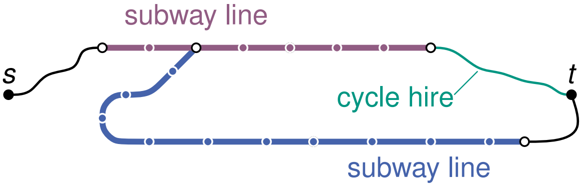
Solution?

Problems of LCSPP



Solution?

Problems of LCSPP

Solution?

Problems of LCSPP

s ? t

- Restrictions must be known in advance
- User might not know them
- Only a single (best?) journey is computed (no alternatives)

Goal: compute a *useful set* of multimodal journeys

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Multicriteria Multimodal Routing [DDP+13]

Idea: compute multicriteria, multimodal Pareto sets

- Optimize arrival time plus
- Various (per mode of transport) „convenience criteria“
  for example # transfers (trains), walking time, taxi costs, etc.

Multicriteria Multimodal Routing [DDP+13]

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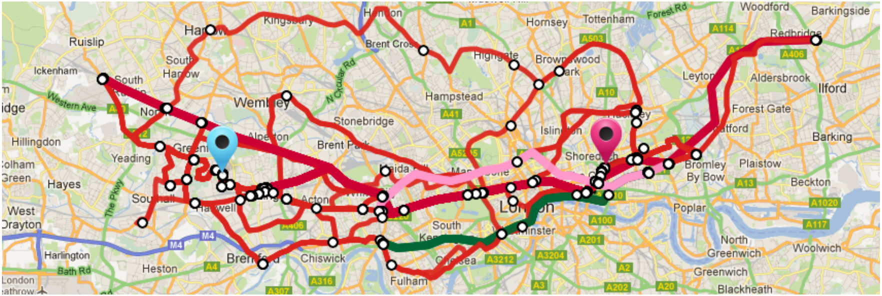
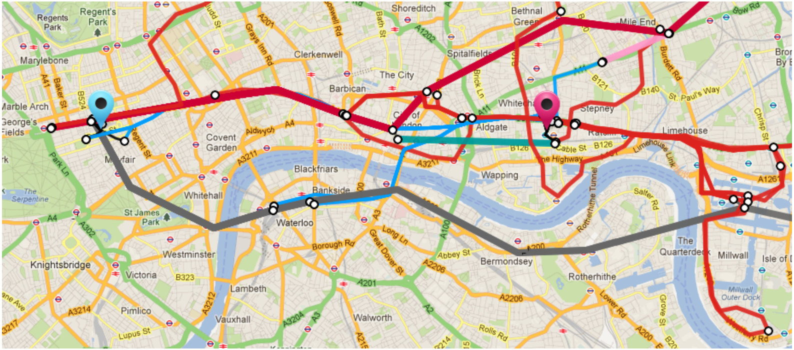


criteria: arrival time, # transfers, walking time **69 journeys**.

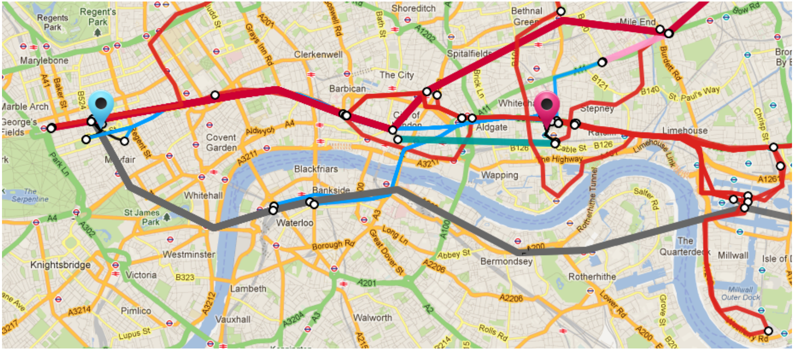
Known problem: Pareto set sizes explode in the number of criteria

Relevant Journeys



- 10 min of walking to arrive 10 sec earlier?
- 1 hour of bus drive to walk 10 sec less?

Relevant Journeys



- 10 min of walking to arrive 10 sec earlier?
- 1 hour of bus drive to walk 10 sec less?
- Rate the journeys using fuzzy logic [FA04]
- Journeys with a higher rating are more relevant

Relevant Journeys

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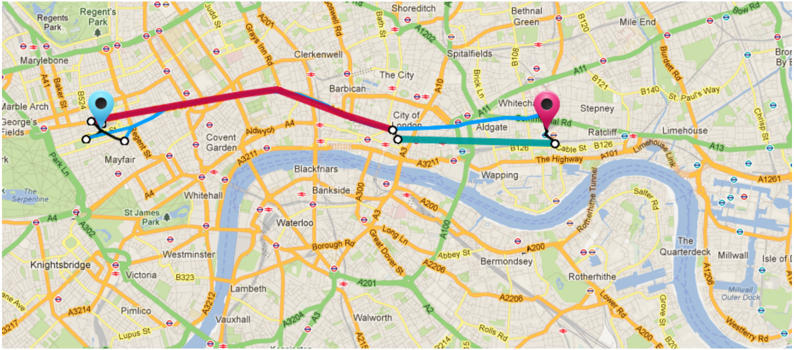

the three top-rated journeys.

- 10 min of walking to arrive 10 sec earlier?
- 1 hour of bus drive to walk 10 sec less?
- Rate the journeys using fuzzy logic [FA04]
- Journeys with a higher rating are more relevant

Reducing the Amount of Work

Problem: queries are slow (> 1 s)

many irrelevant journeys $\Rightarrow$ can we avoid computing them?

Filter already during the algorithm

- MCR-hf: fuzzy filter
- MCR-hb: Pareto filter, but discrete criteria

Restricted walking (arbitrary heuristic)

- MCR-tx-ry: max x minutes of walking between vehicles and max. y at source/target

Reduce the dimension/number of criteria

- MR-x: increase for every x minutes of walking the #transfers by +1

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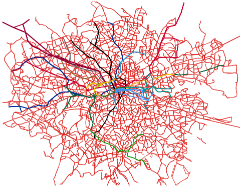
Experimental Evaluation

London, multimodal:

- Roads: 260 k nodes, 1.4 M edges
- Subway, bus, tram, ...
  21 k stops, 5 M connections
- 564 cycle hire station



Criteria: arrival time, # transfers, walking time

Algorithm	# Sol.	Time [ms]	Quality-6 Avg.	Quality-6 Sd.
MCR	29.1	1 438.7	100 %	0 %
MCR-hf	10.9	699.4	89 %	11 %
MCR-hb	9.0	456.7	91 %	10 %
MCR-t10-r15	13.2	885.0	30 %	31 %
MR-10	4.3	39.4	45 %	29 %

Intel Xeon E5-2670, 2.6 GHz, 64 GiB DDR3-1600 RAM, 20 MiB L2 cache

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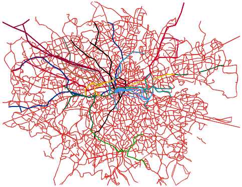

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Conclusion

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Summary

- Algorithm Engineering: combination of theory and practice
- (Very) fast route planning on road and timetable networks
- Considered metric matters
- Multimodal route planning is more expensive
  - Network offers many interesting trade-offs between criteria
  - Multicriteria optimization useful, to allow the user to chose his journey

Outlook

- Formalization of quality for multimodal journeys done?
- Scalability: multimodal multicriteria for worldwide routing?
- Additional questions: delay-robustness, park & ride, . . . ?

Thank you for your attention!

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