Karlsruhe Institute of Technology

Evolution and Evaluation of the Penalty Method for Alternative Graphs

Moritz Kobitzsch, Marcel Radermacher, and Dennis Schieferdecker
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Institute of Theoretical Informatics - Algorithmics

Motivation

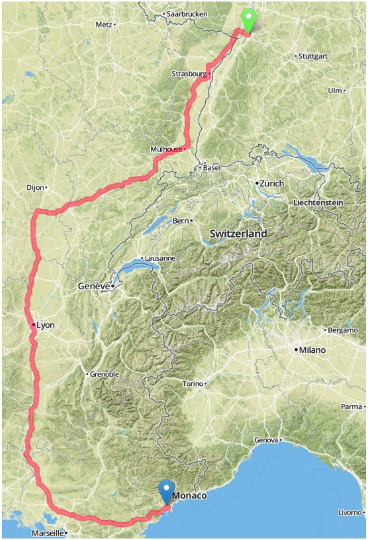
advanced route planning

shortest paths

- multitude of speed-up techniques
  (AF, CH, HL, . . . ; sub-microsecond queries)

alternative routes

- non-optimal routes
  (heuristiccs; quality $\Longleftrightarrow$ speed)
- speed-up techniques do not work well
  (algorithms do not use or relax them)



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Kobitzsch, Radermacher, Schieferdecker:
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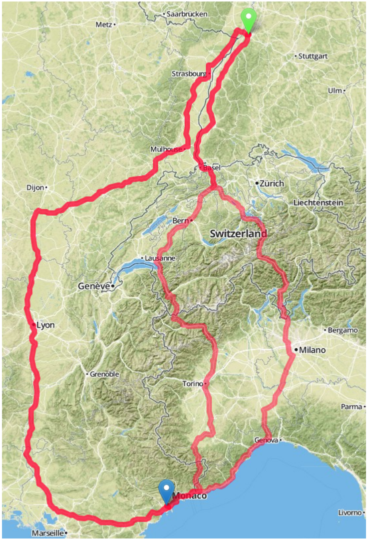

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what are alternative graphs?

alternative graph (AG)

- extension to alternative routes
  - ⇒ encode multiple (good) alternative routes (between one source and one target)
  - ⇒ interaction between alternative routes
  - ⇒ compact representation of options

- intermediate data structure
  - ⇒ sparse, directed graph
  - ⇒ usable with expensive algorithms (stochastic routing, traffic simulation)

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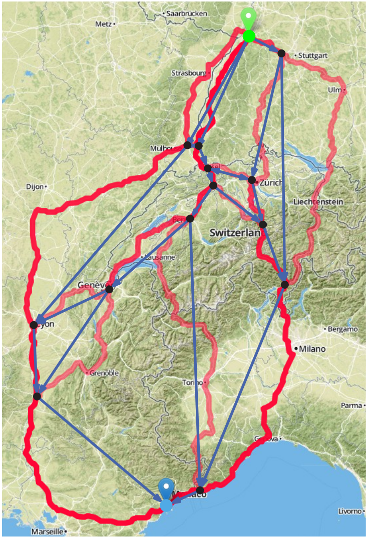

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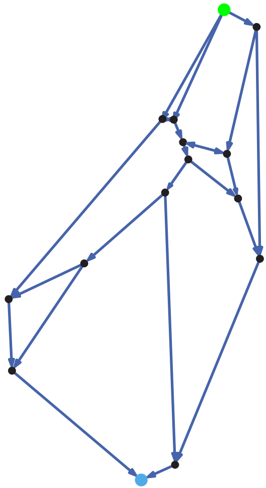


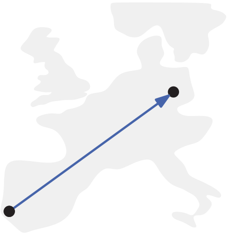
Related Work

what has been done before? (1)

"Alternative Routes in Road Networks"

[ABRAHAM ET AL. 10]

- via-node approach (plateau method)
  - → concatenation of two shortest paths
  - → variants: X-BDV (sec.), X-CHV (millisec.)



quality measures

- not too much longer (stretch)
- sufficiently different (sharing)
- reasonable (local optimality)

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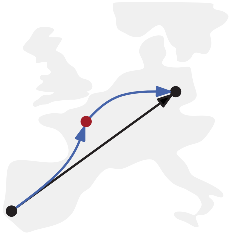

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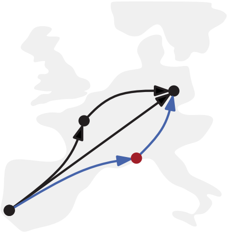

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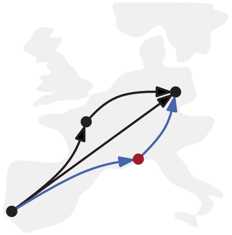

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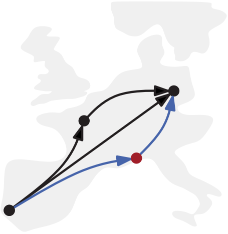

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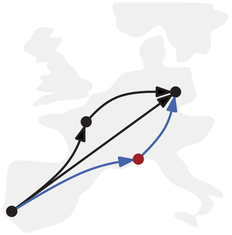

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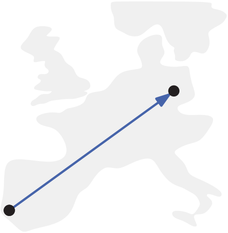
[BADER ET AL. 11]

- penalty method (classical method)
  - → putting penalties on arc costs
  - → based on Dijkstra (sec.)
- no alternative route extraction



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- do not directly translate to quality of alternative routes

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$$totalDist := \sum_{a=(u,v)\in A_H} \frac{c(a)}{\mathcal{D}_H(s,u) + c(a) + \mathcal{D}_H(v,t)}$$

$$averageDist := \frac{\sum_{a\in A_H} c(a)}{\mathcal{D}(s,t)\cdot totalDist}$$

$$\begin{aligned} \text{maximize} \quad & totalDist - (averageDist - 1) \\ \text{s.t.:} \quad & averageDist \le 1.1 \\ & decisionArcs \le 10 \end{aligned}$$

Optimization Potential

what can we do better?

current state-of-the-art

- fast "one-hop" alternative routes
- slow alternative graphs

goal

- fast alternatives with diverse structure

approach

- focus on penalty method
  - ⇒ improve for interactive use (speed-up techniques)
  - ⇒ extract alternative routes (quality criteria similar to via-node approach)
  - ⇒ analyze quality & structure of results

Penalty Method

generic workflow

```
while {termination condition false} do

    {compute shortest path}

    {add penalties to graph}

end

{select shortest paths + combine to alternative graph}

{extract alternative routes}
```

- path selection
- penalization (not covered today)

(modified from previous work)

- fast computation
- alternative route extraction

(not in previous work)

Penalty Method

path selection

basic approach (classical method)

- perform "enough" iterations
  - ⇒ generate set of shortest paths
- select good subset for AG
  (implementation details left open)

when query times matter... (our approach)

- exploit quality measures
  - ⇒ terminate as paths become too long
    (allow maximum stretch w.r.t. original metric)
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    (w.r.t. stretch, sharing measures)

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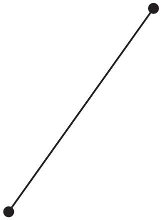

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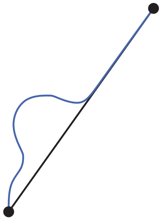

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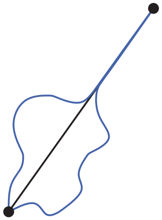

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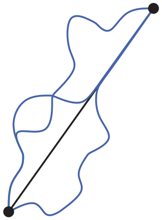

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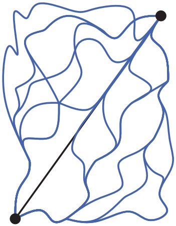

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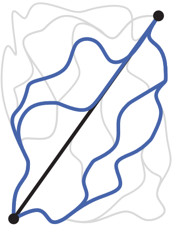

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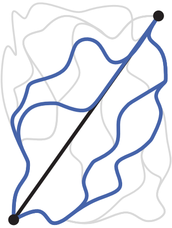

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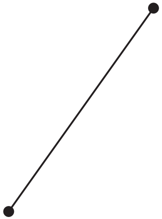

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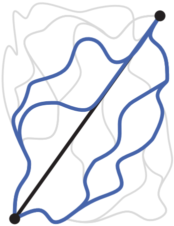

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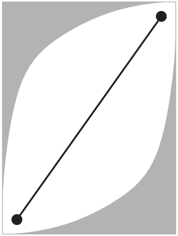

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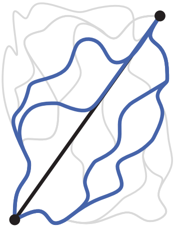

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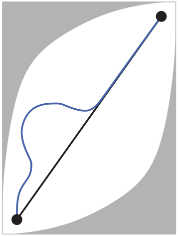

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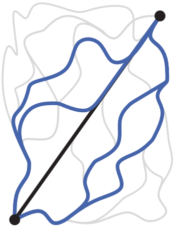

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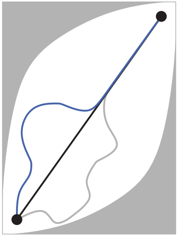

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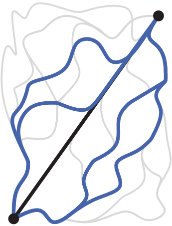

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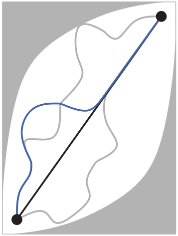

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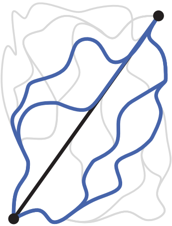

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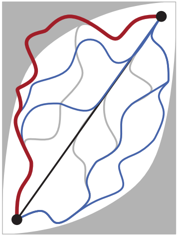

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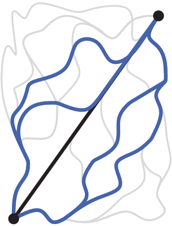

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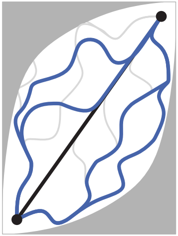

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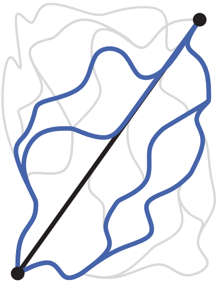

challenges

- compute many shortest paths
  - ⇒ Dijkstra's algorithm [DIJKSTRA 59]
    → used by previous work
    (takes seconds on random queries)
  - ⇒ static speed-up techniques
    (AF, CH, HL, . . . → costly preprocessing)

- arc costs change
  - ⇒ Customizable Route Planning (CRP) [DELLING ET AL. 13]
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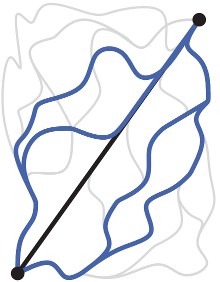

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  - ⇒ but still requires some kind of preprocessing

Penalty Method

computing shortest paths (2)

CRP preprocessing

- structural preprocessing
  - takes minutes to hours
    (required once, can be done offline)
  - multi-level partitioning
  - adding shortcut arcs
    (boundary nodes of each cell become cliques)

- metric customization
  - compute shortcut costs
    (required when arc costs change)
  - takes seconds[1] / tenths of a second[2]
    (using multiple cores and vector units)

Penalty Method

[DELLING ET AL. 13][1]
[DELLING&WERNECK 13][2]

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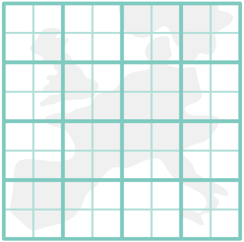

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Karlsruhe Institute of Technology

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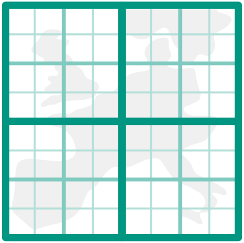

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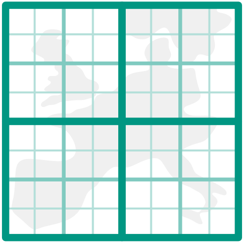

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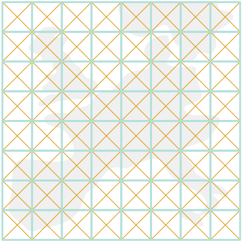

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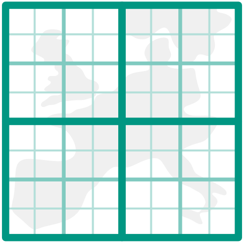

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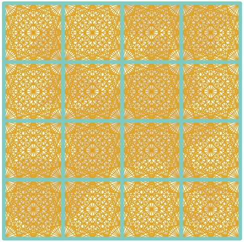

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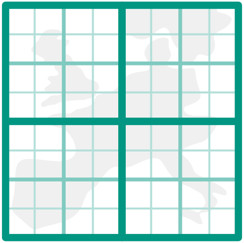

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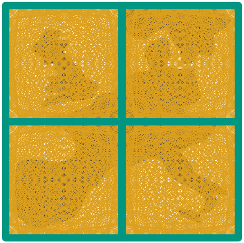
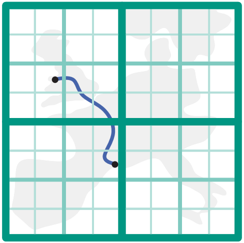


Penalty Method

computing shortest paths (3)



adaptive customization

- only update cells with changes
- only update *k* levels

  ⇒ restrict query algorithm to *k* levels
  ⇒ preprocessing times ⟺ query times
  ⇒ beneficial for short queries (less overhead)

- dynamic level selection

  (depending on hop count, optimized on different query set)

Penalty Method

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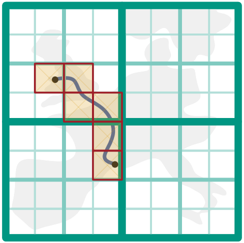

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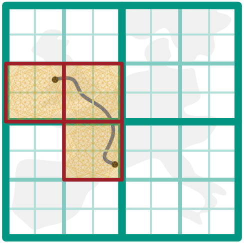

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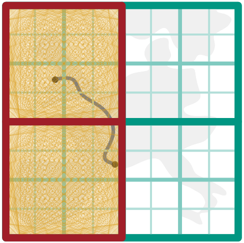

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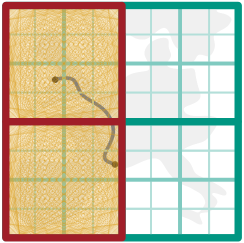

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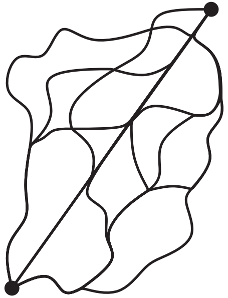
$\Rightarrow$ tens of milliseconds for query and customization

Penalty Method

alternative route extraction (1)

how to extract alternative routes?

- take constituting routes?
  $\Rightarrow$ misses synergy effects
- take any route?
  $\Rightarrow$ arbitrarily bad
- our approach: *CRP-π*
  - two-step procedure
    (via-node & penalty methods)
  - extraction on small graph
    (expensive methods become feasible)



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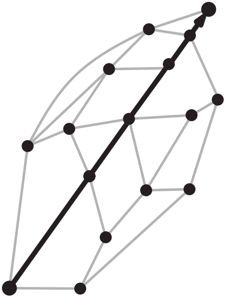

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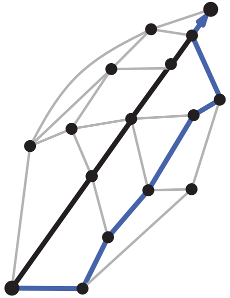

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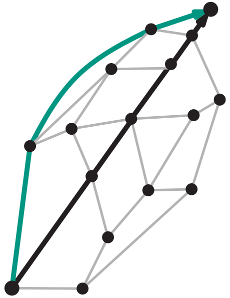

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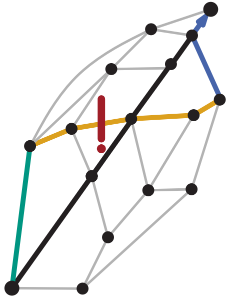

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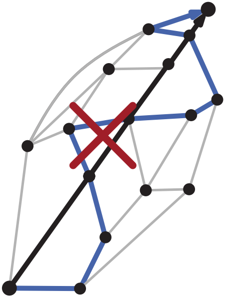
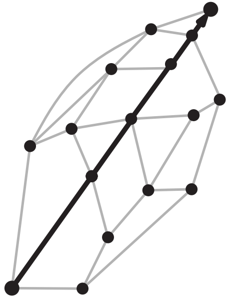


Penalty Method

alternative route extraction (2)

procedure

1. via-node approach
   - based on X-BDV
     → local optimality disabled (not applicable in AG)
   - exhaustively compute routes
   - keep all routes



2. penalty method
   - based on classical penalty method
     → initialize with X-BDV routes
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Penalty Method

alternative route extraction (2)

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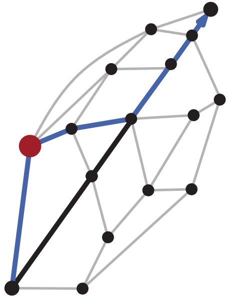

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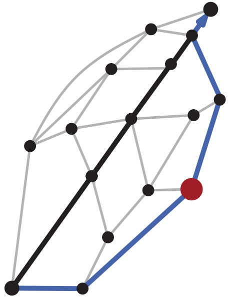

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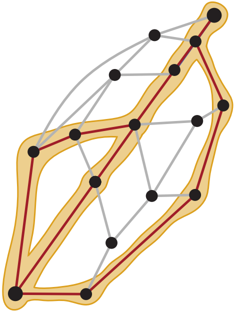

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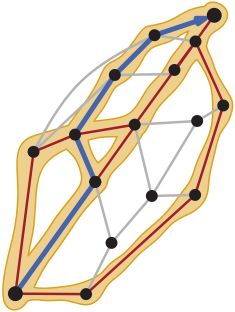

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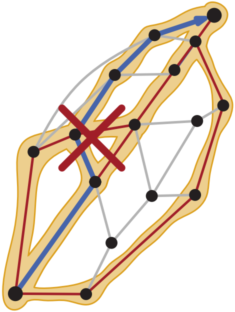

Penalty Method

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Karlsruhe Institute of Technology

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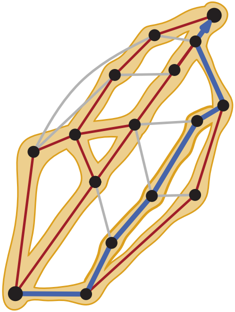

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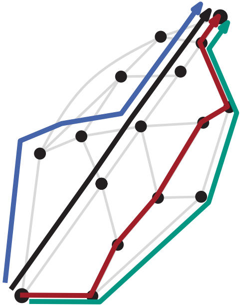


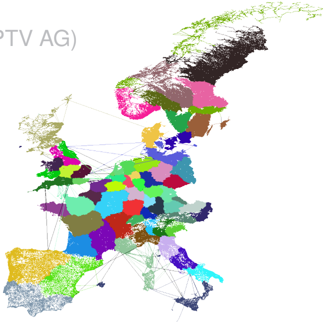
Experimental Setup

hardware/software

- 4 Intel Xeon E5-4640 @ 2.4 GHz, 512 GiB RAM (32 cores, total)
- Ubuntu 12.04, gcc 4.6.1 (full optimizations)

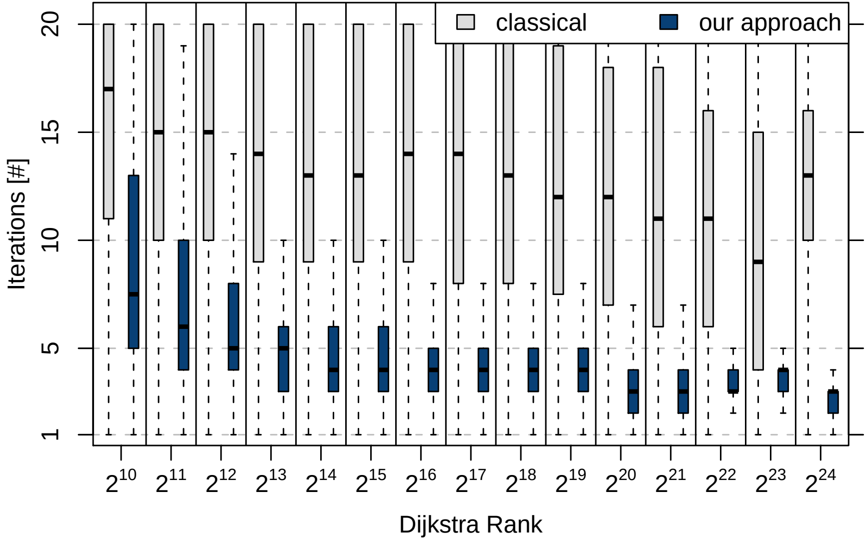
data

- road network of Western Europe (provided by PTV AG)
  - directed, weighted graph, single SCC
  - 18 million vertices, 24 million arcs
    (degree two vertices removed)
  - travel-time metric
- 1 000 queries at random / data point
  (of random Dijkstra rank / of fixed Dijkstra rank)



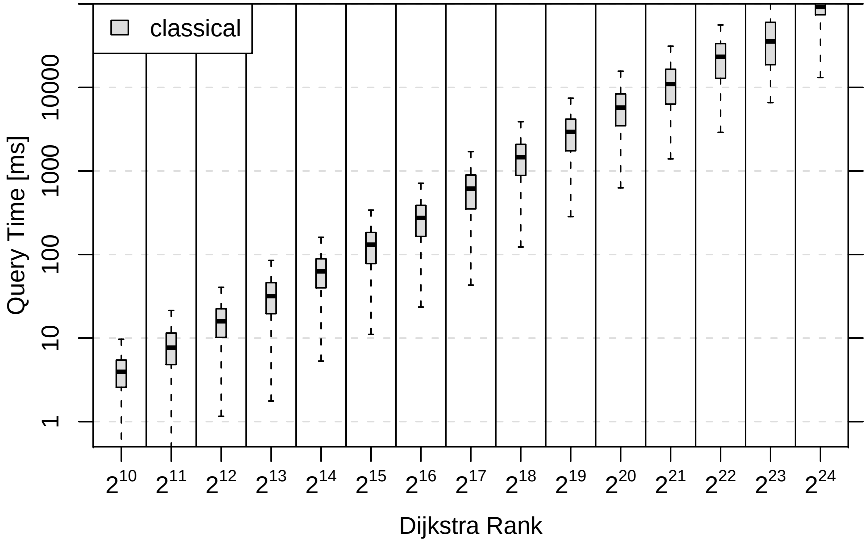
Runtime Analysis

iterations of penalty method



Runtime Analysis

engineering impact



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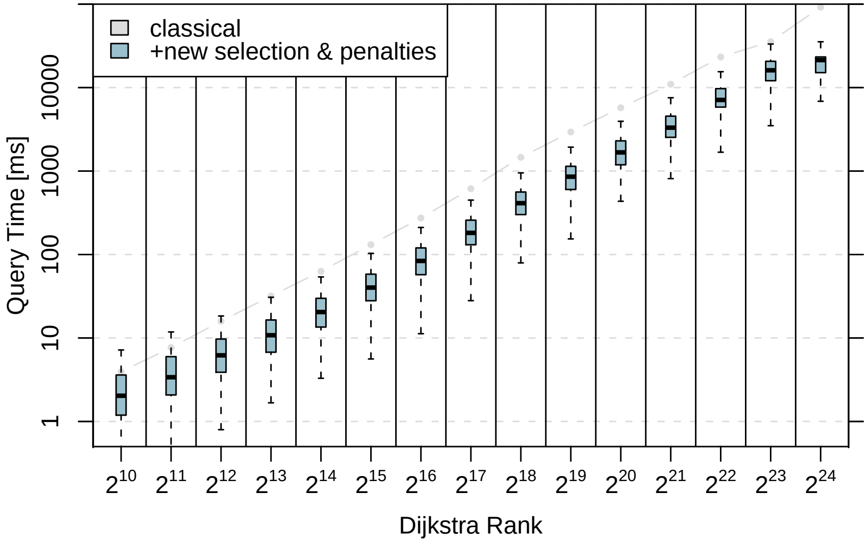

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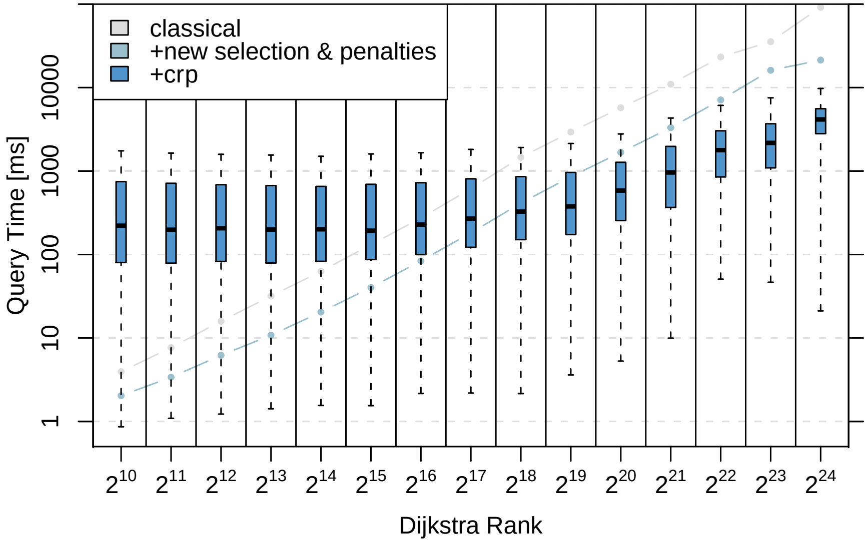

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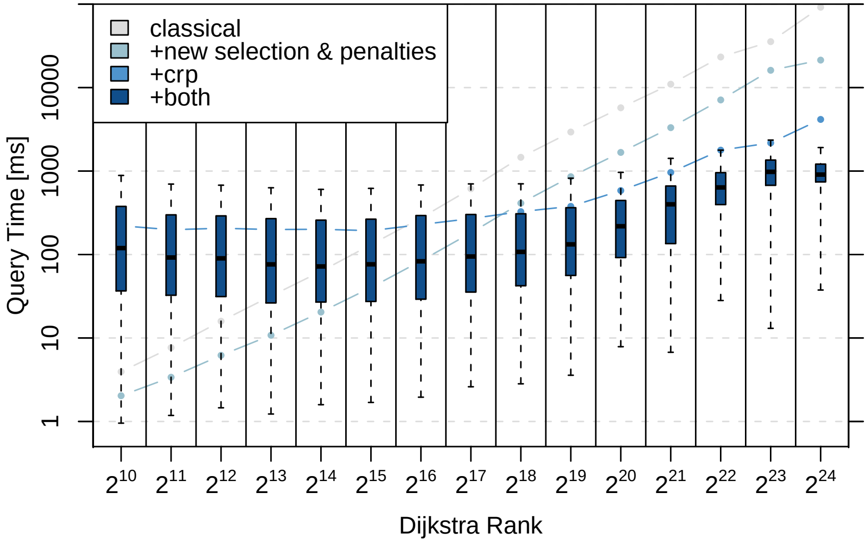

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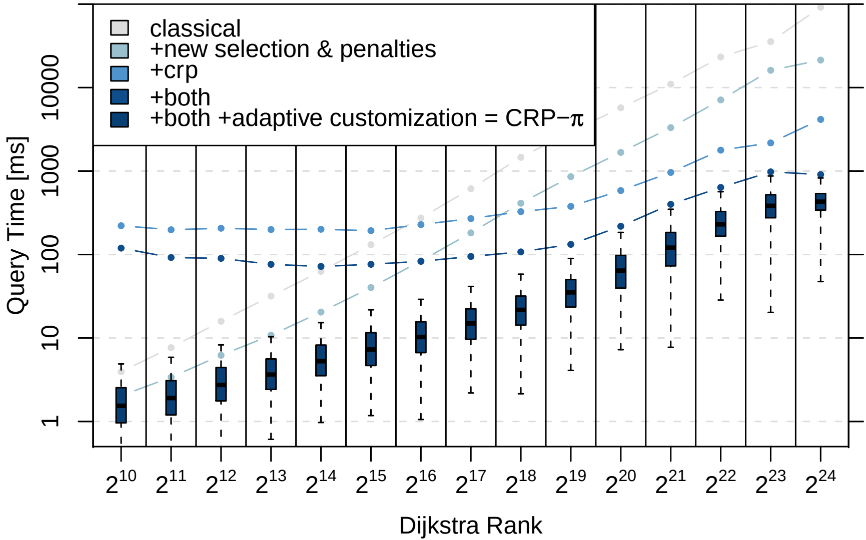
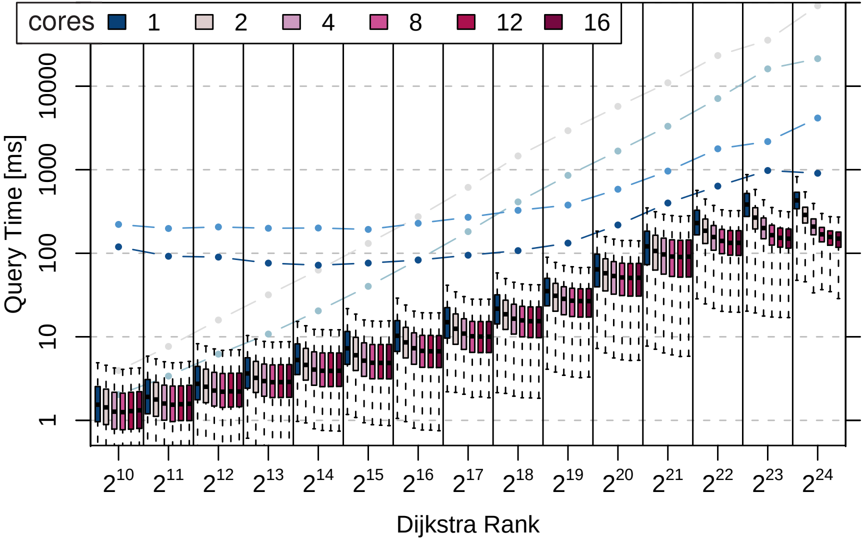


Runtime Analysis

engineering impact – multi-cores



Quality Analysis

alternative graph quality

algorithm	rating	queries	decision arcs
[BADER ET AL. 11]	3.21	100	$\leq$ 10.0
[RADERMACHER 12]	2.89	1 000	7.0
CRP-π	3.32	1 000	(unfiltered) 17.4
CRP-π	2.89	1 000	(filtered) 9.5

- comparable results to previous penalty methods
  - best previous work only considered tiny test set
- filtering to reduce decision arcs ($\approx$100μs)
  - only for comparison to previous penalty methods
  - reduces potential for extracting multiple alternative routes (not applied in subsequent alternative route analysis)

Quality Analysis

alternative route quality

#	algorithm	success [%]	stretch [%]	sharing [%]	optimality [%]
1st	X-BDV	96.0	10.0	41.8	75.4
	X-CHV	89.6	80.4	40.6	68.1
	CRP-π	96.3	42.9	31.9	26.9
2nd	X-BDV	87.6	13.8	59.5	65.1
	X-CHV	72.5	269.0	57.6	57.2
	CRP-π	84.0	47.6	45.9	22.1
3rd	X-BDV	75.5	17.2	65.6	54.6
	X-CHV	51.4	214.0	63.6	46.8
	CRP-π	62.9	67.4	51.8	15.9

- comparable success rates (corresponds to runtimes)
- reasonable path quality measures (lower stretch $\Longleftrightarrow$ higher sharing)
- limited similarity to via-node alternativs (77.9% | 72.7% | 65.5%)

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2nd	X-BDV	87.6	13.8	59.5	65.1
	X-CHV	72.5	269.0	57.6	57.2
	CRP-π	84.0	47.6	45.9	22.1
3rd	X-BDV	75.5	17.2	65.6	54.6
	X-CHV	51.4	214.0	63.6	46.8
	CRP-π	62.9	67.4	51.8	15.9

- comparable success rates (corresponds to runtimes)
- reasonable path quality measures (lower stretch $\Longleftrightarrow$ higher sharing)
- limited similarity to via-node alternativs (77.9% | 72.7% | 65.5%)

Conclusion

Summary

- first fast implemenation of penalty method, suited for interactive use
  (utilizing vector units and multi-core capabilities of modern CPUs)
- extracted routes of high quality, and distinct from via-node approach
  (first quantitative analysis of extracted routes from alternative graphs)

Open Problems

- general classification scheme for good alternatives
  (set of criteria, not tailored to a specific approach)
- improve runtime to compete with via-node approach
  (combination with [PARASKEVOPOULOS&ZAROLIAGIS 13] seems promising)

Thank you for your attention!

Time for questions!

References

[DIJKSTRA 59]
A Note on Two Problems in Connexion with Graphs

[ABRAHAM ET AL. 10]
Alternative Routes in Road Networks

[BADER ET AL. 11]
Alternative Route Graphs in Road Networks

[DELLING ET AL. 13]
Customizable Route Planning

[DELLING&WERNECK 13]
Faster Customization of Road Networks

[PARASKEVOPOULOS&ZAROLIAGIS 13]
Improved Alternative Route Planning

[RADERMACHER 12]
Schnelle Berechnung von Alternativgraphen

Appendix

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backup slides

Motivation

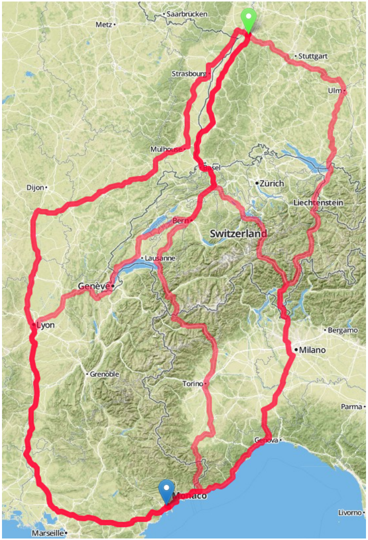
why consider alternative routes?

business perspective

- provide options
  (users have varied preferences)
- overcome flaws in model and data
  (shortest paths need not be best in reality)

research perspective

- building blocks
  (traffic simulation, stochastic routing)
- hard optimization problems
  (quality guarantees)



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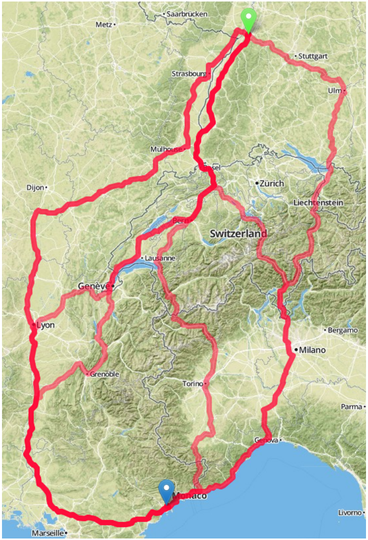

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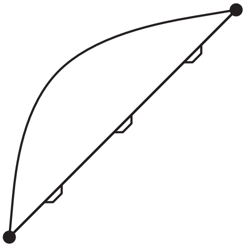
Related Work

peering into the distant past...

Karlsruhe Institute of Technology

simple approaches to find distinct routes

- *k*-shortest path
  (meaningful alternatives only for large *k*)
- multi-criteria optimization
  (distance $\Longleftrightarrow$ difference)
- time-dependent routes
  (alternatives not guaranteed, limited data)



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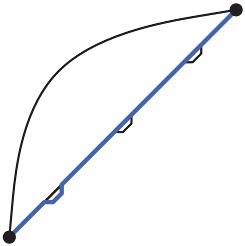

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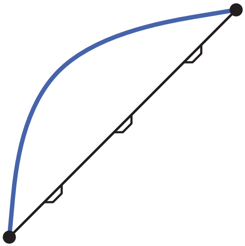

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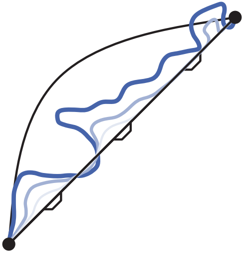

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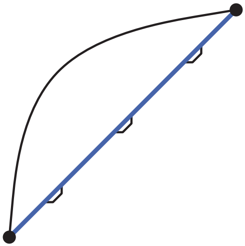

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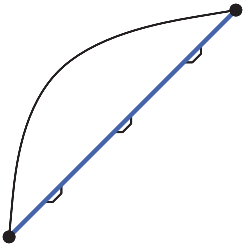

insufficient solutions to the problem

Penalty Method

penalization (1)

requirements

- enable discovery of diverse routes
  - ⇒ penalties on arcs of current route
    (discourage previous routes)
  - ⇒ penalties on adjoined arcs
    (discourage meandering)

- quick discovery of diverse routes
  - ⇒ generate lots of new information in each iteration
  - ⇒ speed $\Longleftrightarrow$ quality

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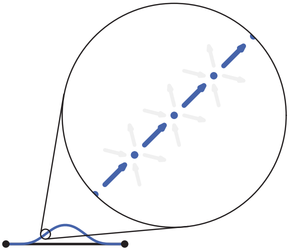

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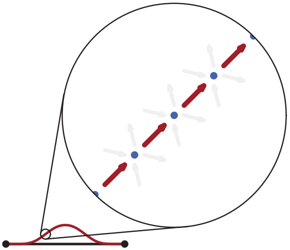

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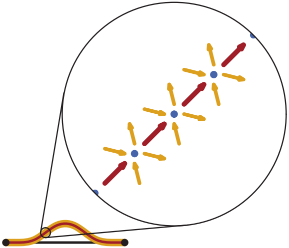

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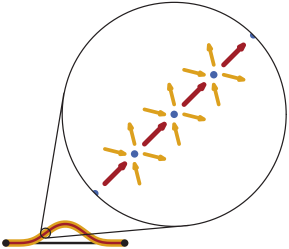

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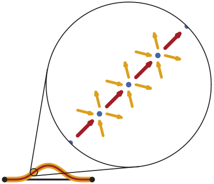
⇒ how to choose penalty values?

Penalty Method

penalization (2)



additive penalties (classical method)

- add fraction of arc/path costs (w.r.t. original metric)
  $\Rightarrow$ shortest paths only change slowly

geometrically growing penalties (our approach)

- multiply arc costs on current route by small factor
  $\Rightarrow$ often used paths quickly become undesirable
- add $\frac{1}{2}\sqrt{\text{(current route cost)}}$ to adjoined arc costs
  $\Rightarrow$ discourages short detours on long routes

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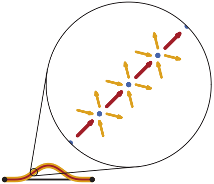

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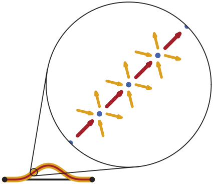

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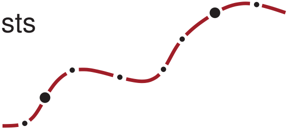

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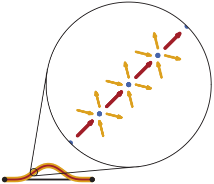

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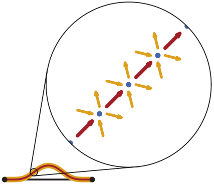

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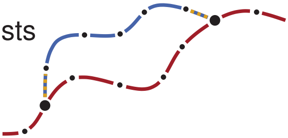
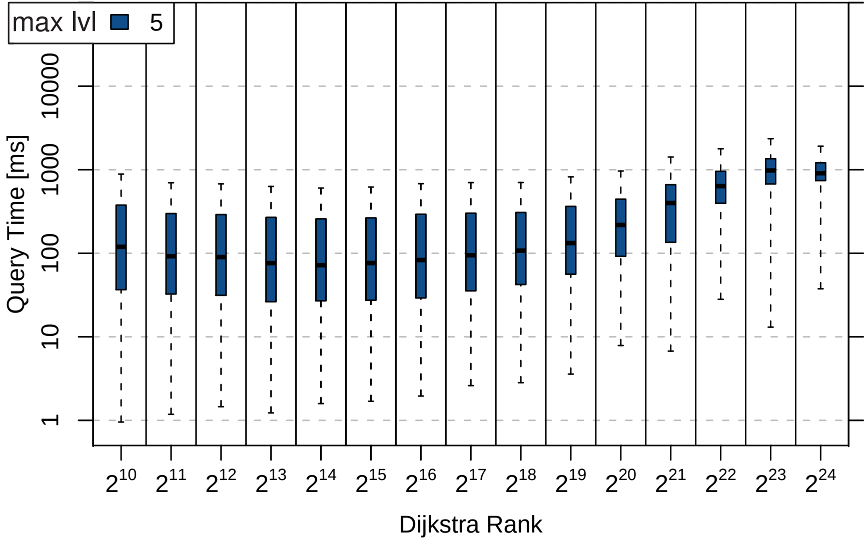


Runtime Analysis

restriction of maximum crp level



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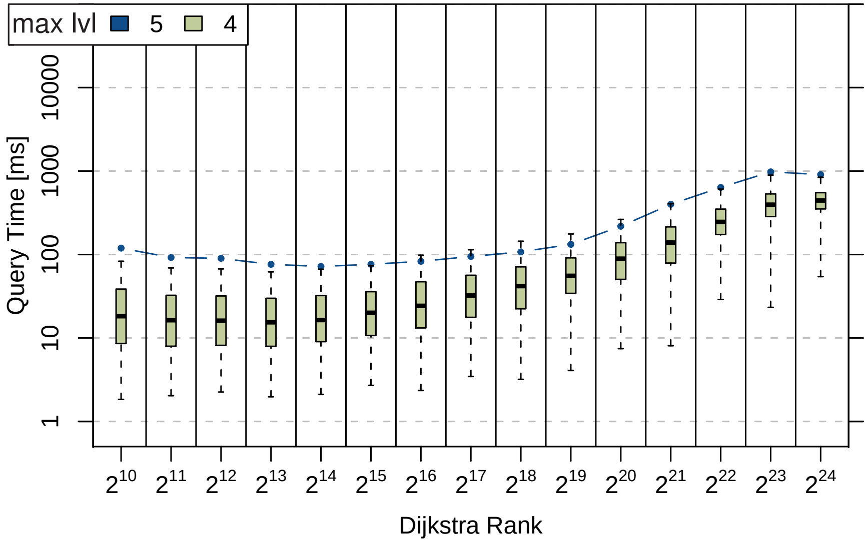

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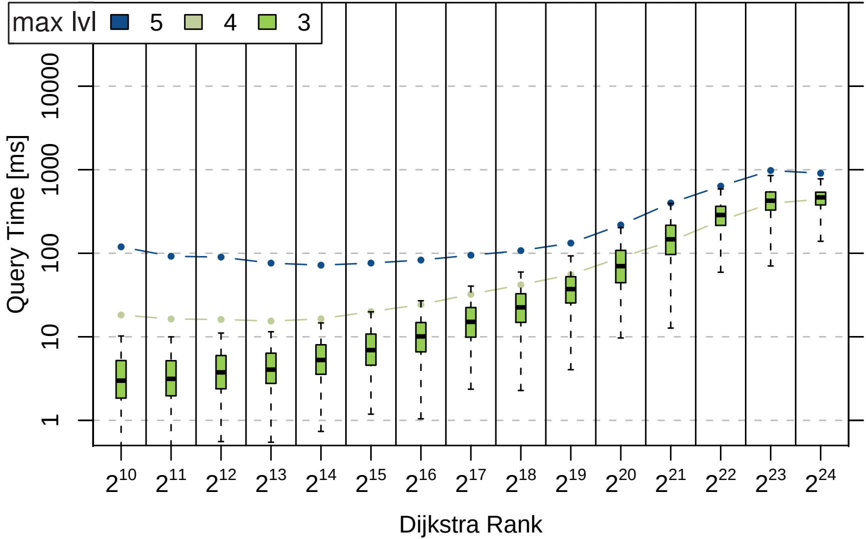

Kobitzsch, Radermacher, Schieferdecker:
Evolution and Evaluation of the Penalty Method for Alternative Graphs

Institute of Theoretical Informatics
Algorithmics

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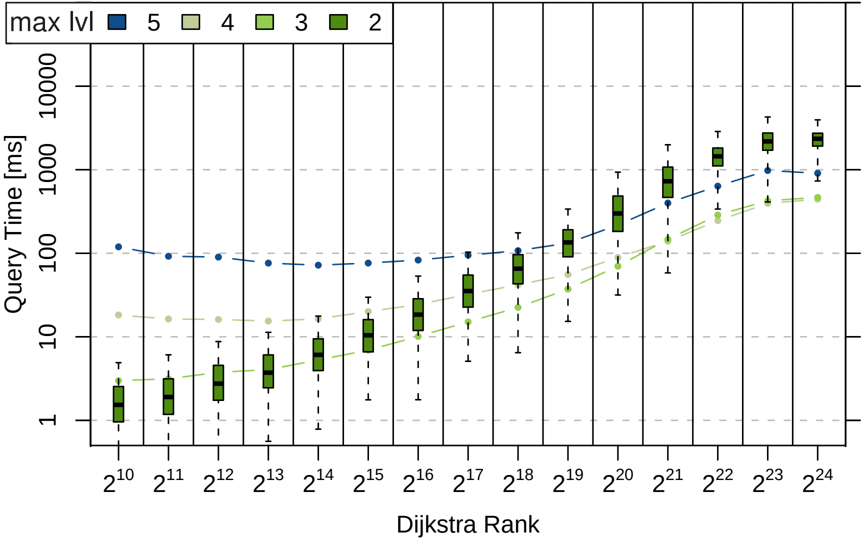

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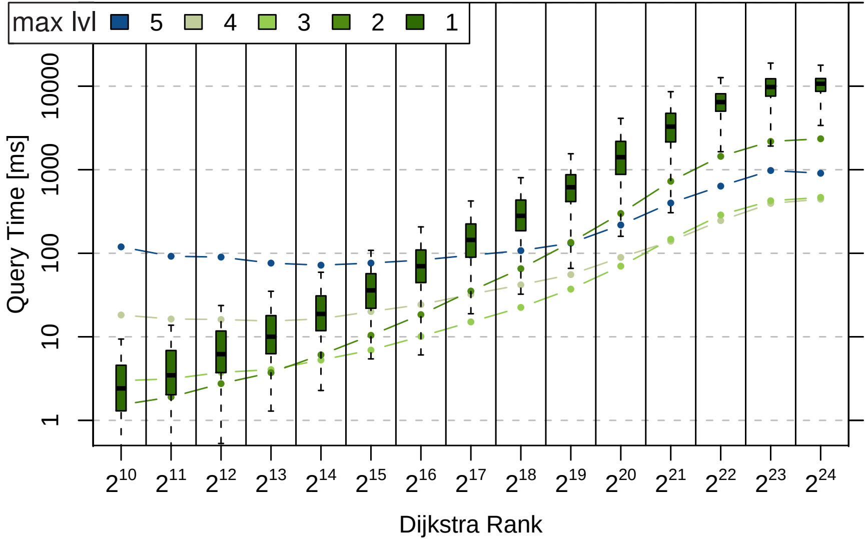

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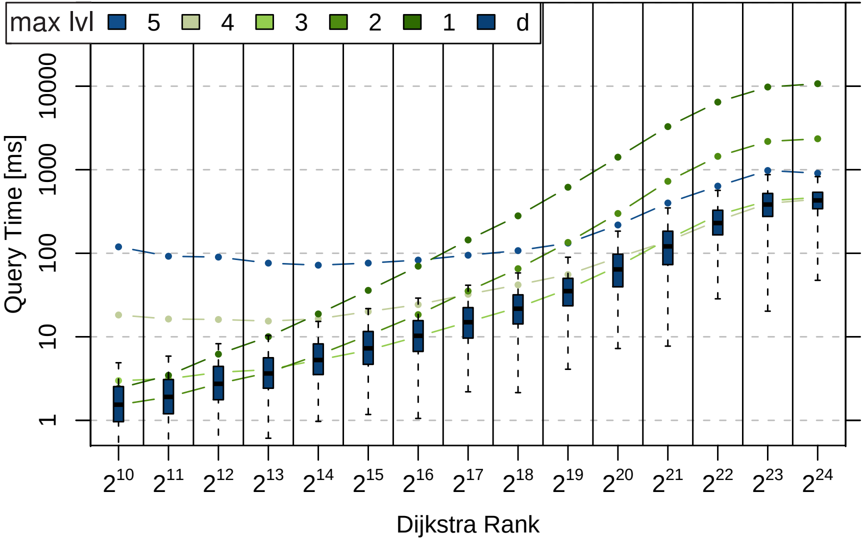
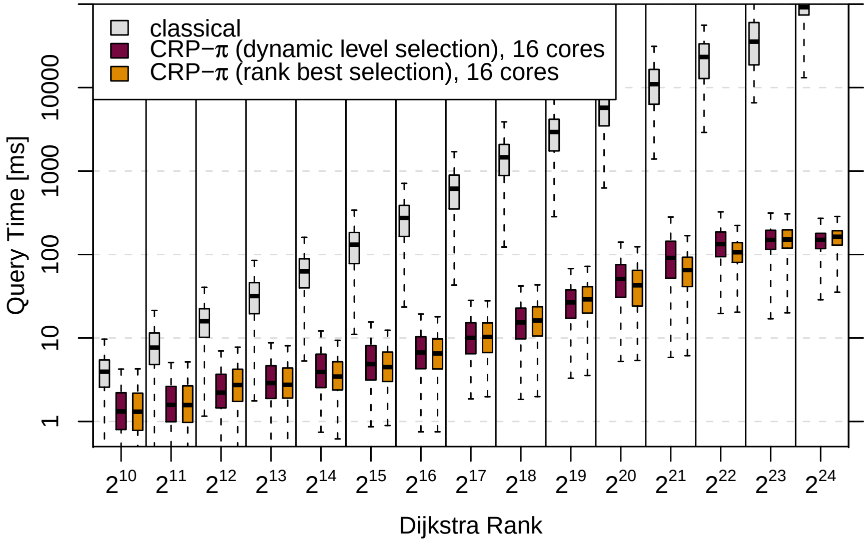


Runtime Analysis

optimal selection of maximum crp level



Quality Analysis

alternative route structure

differences between penalty & via-node alternatives

- procedure
  - consider all CRP-π routes
  - for each, find via-node alternative with most overlap
    (test each vertex on CRP-π route as via-node)
- average maximum overlap
  - 77.9% | 72.7% | 65.5% (1st – 3rd alternative)
  - higher order alternatives increasingly distinct
    (first routes likely extracted by via-node approach)

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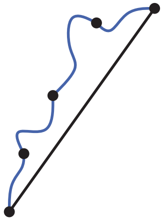

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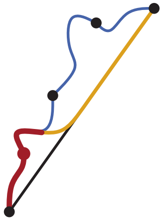

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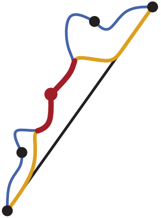

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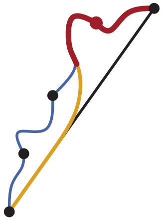

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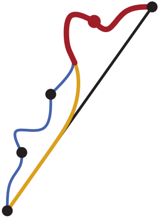

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$\Rightarrow$ CRP-π provides distinct routes a via-node approach cannot find